



**Calhoun: The NPS Institutional Archive**  
**DSpace Repository**

---

Theses and Dissertations

1. Thesis and Dissertation Collection, all items

---

1991-06

# Implementation of multi-frequency modulation with trellis encoding and Viterbi decoding using a digital signal processing board

Wisniewski, John W.

Monterey, California. Naval Postgraduate School

---

<http://hdl.handle.net/10945/30967>

---

This publication is a work of the U.S. Government as defined in Title 17, United States Code, Section 101. Copyright protection is not available for this work in the United States.

*Downloaded from NPS Archive: Calhoun*



Calhoun is the Naval Postgraduate School's public access digital repository for research materials and institutional publications created by the NPS community. Calhoun is named for Professor of Mathematics Guy K. Calhoun, NPS's first appointed -- and published -- scholarly author.

**Dudley Knox Library / Naval Postgraduate School**  
**411 Dyer Road / 1 University Circle**  
**Monterey, California USA 93943**

<http://www.nps.edu/library>

AD-A245 998



# NAVAL POSTGRADUATE SCHOOL

## Monterey, California



# THESIS

DTIC  
SELECTE  
FEB 18 1992  
S B D

Implementation of Multi-Frequency Modulation  
with Trellis Encoding and Viterbi Decoding  
Using a Digital Signal Processing Board

by

John W. Wisniewski

June 1991

Thesis Advisor:

P.H. Moose

Approved for public release; distribution is unlimited.

92-03678



UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE				Form Approved OMB No. 0704-0188	
1a. REPORT SECURITY CLASSIFICATION <b>UNCLASSIFIED</b>			1b. RESTRICTIVE MARKINGS		
2a. SECURITY CLASSIFICATION AUTHORITY			3. DISTRIBUTION / AVAILABILITY OF REPORT Approved for public release; distribution is unlimited		
2b. DECLASSIFICATION / DOWNGRADING SCHEDULE					
4. PERFORMING ORGANIZATION REPORT NUMBER(S)			5. MONITORING ORGANIZATION REPORT NUMBER(S)		
6a. NAME OF PERFORMING ORGANIZATION <b>Naval Postgraduate School</b>		6b. OFFICE SYMBOL (If applicable) <b>32</b>	7a. NAME OF MONITORING ORGANIZATION <b>Naval Postgraduate School</b>		
6c. ADDRESS (City, State, and ZIP Code) <b>Monterey, California 93943-5000</b>			7b. ADDRESS (City, State, and ZIP Code) <b>Monterey, California 93943-5000</b>		
8a. NAME OF FUNDING / SPONSORING ORGANIZATION		8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER		
8c. ADDRESS (City, State, and ZIP Code)			10. SOURCE OF FUNDING NUMBERS		
PROGRAM ELEMENT NO.		PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO.	
11. TITLE (Include Security Classification) <b>IMPLEMENTATION OF MULTI-FREQUENCY MODULATION WITH TRELIS ENCODING AND VITERBI DECODING USING A DIGITAL SIGNAL PROCESSING BOARD</b>					
12. PERSONAL AUTHOR(S) <b>WISNIEWSKI, John William</b>					
13a. TYPE OF REPORT <b>Master's Thesis</b>		13b. TIME COVERED FROM _____ TO _____		14. DATE OF REPORT (Year, Month, Day) <b>1991 June</b>	
15. PAGE COUNT <b>95</b>					
16. SUPPLEMENTARY NOTATION <b>The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.</b>					
17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)		
FIELD	GROUP	SUB-GROUP	<b>Communication; Multi-Frequency Modulation; Trellis coding; Viterbi decoding</b>		
19. ABSTRACT (Continue on reverse if necessary and identify by block number)  <b>Multi-Frequency Modulation Has been the topic of several papers at NPS. In past systems the majority of time required for the generation of the MFM signal was due to the software routine used to implement the FFT. In this report a Digital Signal Processor was used to generate the FFT. The use of Trellis coding and Viterbi decoding on a Digital Signal Processor was also investigated. Assembly language programs for three encoder/decoder systems were developed. The first uses a 16 QAM signal, the second uses a 2/3 rate convolutional encoder and Viterbi decoder and the third uses the CCITT V.32 convolutional encoder and Viterbi decoder.</b>					
20. DISTRIBUTION / AVAILABILITY OF ABSTRACT <input checked="" type="checkbox"/> UNCLASSIFIED/UNLIMITED <input type="checkbox"/> SAME AS RPT. <input type="checkbox"/> DTIC USERS			21. ABSTRACT SECURITY CLASSIFICATION <b>UNCLASSIFIED</b>		
22a. NAME OF RESPONSIBLE INDIVIDUAL <b>MOOSE, P. H.</b>			22b. TELEPHONE (Include Area Code) <b>(408)-646-2838</b>		22c. OFFICE SYMBOL <b>EC/Me</b>

Approved for public release; distribution is unlimited.

Implementation of Multi-Frequency Modulation  
with Trellis Encoding and Viterbi Decoding  
Using a Digital Signal Processing Board

by

John W. Wisniewski  
Lieutenant, United States Navy  
B.S.E.E., Virginia Military Institute

Submitted in partial fulfillment  
of the requirements for the degree of

MASTER OF SCIENCE IN ELECTRICAL ENGINEERING

from the

NAVAL POSTGRADUATE SCHOOL  
June 1991

Author:

[REDACTED]

John W. Wisniewski

Approved by:

[REDACTED]

P. H. Moose, Thesis Advisor

[REDACTED]

T. T. Ha, Second Reader

[REDACTED]

Michael A. Morgan, Chairman  
Department of Electrical and Computer Engineering

## ABSTRACT

Multi-Frequency Modulation has been the topic of several papers at NPS. In past systems the majority of time required for the generation of the MFM signal was due to the software routine used to implement the FFT. In this report a Digital Signal Processor was used to reduce the time needed to generate the FFT. The use of Trellis coding and Viterbi decoding on a Digital Signal Processor was also investigated. Assembly language programs for three encoder/decoder systems were developed. The first uses a 16 QAM signal, the second uses a 2/3 rate convolutional encoder and Viterbi decoder and the third uses the V.32 convolutional encoder and a Viterbi decoder.



Accession For	
NTIS GRA&I	<input checked="checked" type="checkbox"/>
DTIC TAB	<input type="checkbox"/>
Unannounced	<input type="checkbox"/>
Justification	
By	
Distribution/	
Availability Codes	
Dist	Avail and/or Special
A-1	

## DISCLAIMER

Some of the terms used in this thesis are registered trademarks of commercial products. Rather than attempt to cite each occurrence of a trademark, all trademarks appearing in this thesis are listed below following the name of the firm holding the trademark.

Ariel Corporation . . . . . Ariel, PC-56, PC-56D, BUG-56

Borland International, Inc. . . . . Turbo Pascal

The Math Works, Inc. . . . . Matlab

Microsoft Corporation . . . . . Microsoft C

Motorola, Inc. . . . . Motorola

The reader is cautioned that computer programs developed in this research may not have been exercised for all cases of interest. While every effort has been made, within the time available, to ensure that the programs are free of computational and logical errors, they cannot be considered validated. Any application of these programs without additional verification is at the risk of the user.

## TABLE OF CONTENTS

I.	INTRODUCTION . . . . .	1
II.	THEORY . . . . .	4
	A. MULTI-FREQUENCY MODULATION . . . . .	4
	B. TRELLIS CODED MODULATION . . . . .	6
	C. VITERBI DECODER . . . . .	10
III.	SYSTEM DEVELOPMENT . . . . .	13
	A. ENCODERS . . . . .	16
	1. 16 QAM Encoder . . . . .	16
	2. 2/3 Rate Convolutional Encoder . . . . .	16
	3. V.32 Convolutional Encoder . . . . .	18
	B. GENERATING THE MFM SIGNAL . . . . .	19
	C. DECODERS . . . . .	20
	1. 16 QAM DECODER . . . . .	20
	2. 2/3 Rate Code Decoder . . . . .	21
	3. V.32 DECODER . . . . .	22
IV.	SYSTEM OPERATION . . . . .	24
V.	CONCLUSIONS . . . . .	26

APPENDIX A.	FFT . . . . .	28
APPENDIX B.	IFFT . . . . .	32
APPENDIX C.	SINE COSINE GENERATOR . . . . .	36
APPENDIX D.	16 QAM DATA FILES . . . . .	37
APPENDIX E.	16 QAM ENCODER . . . . .	38
APPENDIX F.	16 QAM BOUNDARY FILE . . . . .	41
APPENDIX G.	16 QAM DECODER . . . . .	42
APPENDIX H.	2/3 RATE CODE DATA FILES . . . . .	47
APPENDIX I.	2/3 RATE CODE ENCODER . . . . .	48
APPENDIX J.	2/3 RATE CODE BOUNDARY FILE . . . . .	51
APPENDIX K.	2/3 RATE CODE VITERBI DECODER . . . . .	52
APPENDIX L.	V.32 DATA FILES . . . . .	62
APPENDIX M.	V.32 ENCODER . . . . .	63



APPENDIX N. V.32 BOUNDARY FILE . . . . .	67
APPENDIX O. V.32 VITERBI DECODER . . . . .	70
LIST OF REFERENCES . . . . .	84
BIBLIOGRAPHY . . . . .	85
INITIAL DISTRIBUTION LIST . . . . .	86

## I. INTRODUCTION

There has long been an interest in frequency division multiplexing as a means of combatting impulsive noise, avoiding equalization and making fuller use of the bandwidth available. The principle for Multi-Frequency Modulation (MFM) was first used over thirty years ago in the Collins Kineplex system. Since that time MFM has been used under many names:

- multiplexed Quadrature Amplitude Modulation (QAM)
- orthogonal Frequency Division Multiplexing (FDM)
- dynamically assigned QAM
- multicarrier modulation

A parallel or multiplexed data system offers the potential to reduce some of the problems of serial systems. In order to increase the data rate in a serial system you must utilize higher order modulation or decrease the symbol interval, increasing the bandwidth, at the risk of degrading the performance of the system. In a parallel data system several sequential streams of data are transmitted simultaneously. In a classical parallel data system there are  $N$  non-overlapping subchannels with each data element occupying only a small portion of the available bandwidth.

With the continuing development of Digital Signal Processing technology there has been renewed interest in MFM for possible use in:

- General Switched Telephone Network (GSTN)
- 60-108 Khz Frequency-division Multiplexed (FDM) group band

- Cellular radio
- High speed data for transmission on the high-rate digital subscriber line (HDSL)

Multi-Frequency Modulation (MFM) can easily be implemented on a computer due to the minimal requirements of hardware to construct a transmitter or receiver. The primary components of a MFM transmitter/receiver are D/A, A/D converters and a method for computing an FFT. MFM has been the topic of several papers and projects at NPS using various techniques for data acquisition and modulation. One of the primary problems with implementing an MFM system in past projects, has been the time required to perform an FFT using current software routines. With the continuing development of Digital Signal Processing (DSP) chips there exist a great number of DSP boards complete with D/A, A/D converters, filters, and memory available for industry standard computers. This provides the capability to purchase an off the shelf item that has all the necessary components to implement an MFM transmitter/receiver. Utilizing a DSP board for the computation of the FFT's required for MFM provides a tremendous performance gain over the software routines that were used in previous projects. Once the programs are downloaded, the performance of the DSP board is independent of the performance of the host computer.

General purpose Digital Signal Processor chips, such as the Motorola DSP 56001 (which was used in the development of the programs included), have an architecture ideally suited to the rapid calculation of FFTs. The 56001 is a fixed point Digital Signal Processor which has three internal memory and address busses which allow the execution of instructions with

parallel data moves to the X and Y memory locations. This allows the rapid execution of complex computations. There are also 256 locations of X and Y Rom that contain Mu-law and A-law expansion tables as well as a full four quadrant sine wave table.

The first objective of this project is to investigate the use of a DSP for implementing an MFM system and reduce the time required to generate a MFM signal. The second objective was to investigate the use of trellis coding and Viterbi decoding using a Digital Signal Processor.

## II. THEORY

### A. MULTI-FREQUENCY MODULATION

A Multi-Frequency Modulated signal has a packet structure and is comprised of time and frequency slots. (Figure 1)

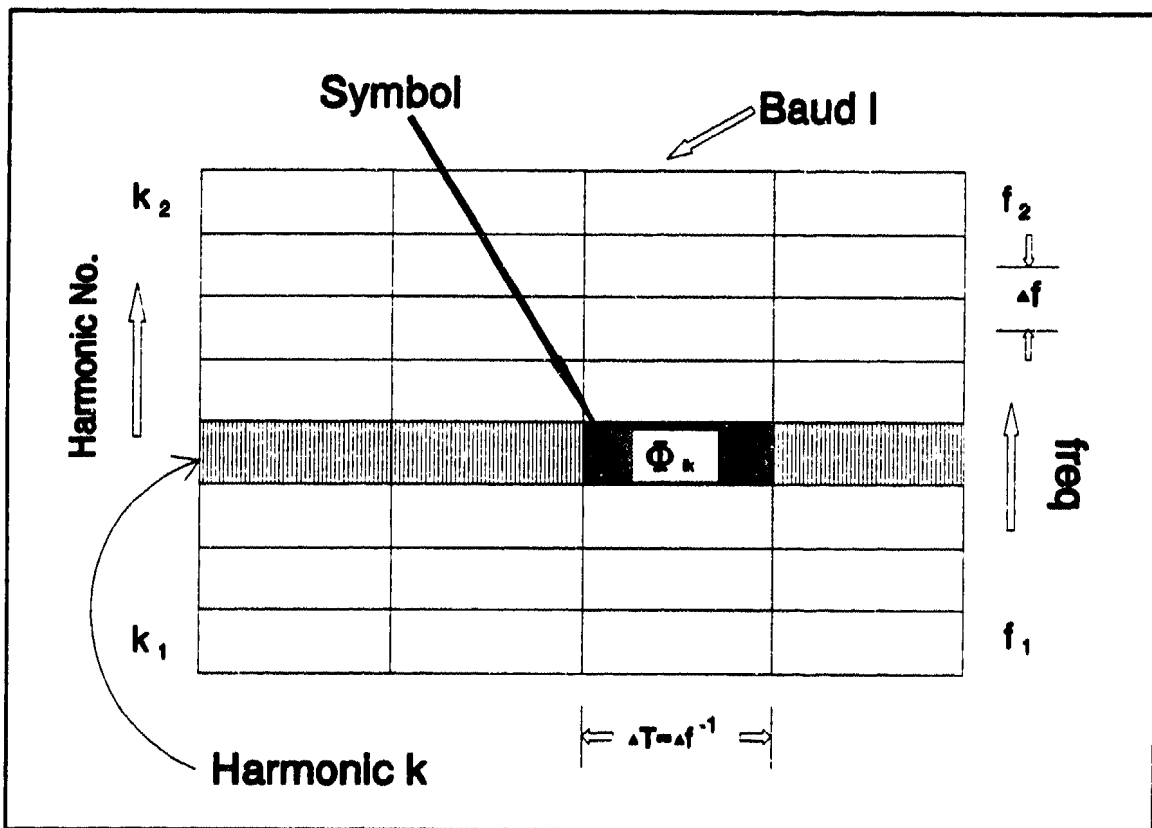


Figure 1 MFM Signal Packet (from Ref. 1: p.3)

The following definitions will be used for discussing MFM: [Ref. 1: pp 5-6]

- $K$ : Number of MFM tones
- $T$ : Packet length in seconds

- $\Delta T$ : Baud length in seconds
- $k_x$ : Baud length in number of samples
- $L$ : Number of bauds per packet
- $\Delta t$ : Time between samples in seconds
- $f_x = 1/\Delta t$ : Sampling or clock frequency for D/A and A/D conversion in Hz
- $\Delta f = 1/\Delta T$ : Frequency spacing (minimum) between MFM tones
- $\phi_{1k}$ : Symbol set. Phase of the  $k^{\text{th}}$  tone in the  $1^{\text{th}}$  baud
- $A_{1k}$ : Amplitude of the  $k^{\text{th}}$  tone in the  $1^{\text{th}}$  baud

Each MFM packet consists of  $L$  bauds of  $K$  tones. The packet construction for the  $1^{\text{th}}$  baud is given by:[Ref 1: pp 6-7]

$$x_1(u) = \sum_k x_{1k}(u) \quad (1)$$

where, the analog representation of each tone during the  $1^{\text{th}}$  baud is given by:

$$x_{1k}(u) = A_{1k} \cos(2\pi k \Delta f u + \phi_{1k}) \quad ; 0 \leq u \leq \Delta T \quad (2)$$

The time  $u$ , is referenced from the beginning of the baud. The time at the beginning of the baud is defined as  $t_0$  and the time at any given point in the packet is  $t = t_0 + L\Delta T + u$ .

By sampling (1) and (2) at intervals  $\Delta t = 1/f_x$  a discrete time sampled version for the  $1^{\text{th}}$  baud can be found:

$$x_1(n) = \sum_k x_{1k}(n) \quad (3)$$

where the discrete time version of each tone during the 1<sup>th</sup> baud is given by:

$$x_{1k}(n) = A_{1k} \cos(2\pi kn/k_x + \phi_{1k}) ; 0 \leq n \leq k_x - 1 \quad (4)$$

The value,  $n$ , is the discrete time referenced to the beginning of the baud. From the Sampling Theorem the maximum frequency must be less than  $f_x/2$ . There are a maximum of  $k_x/2$  tones available spaced at intervals of  $\Delta f$  between dc and  $f_x/2 - \Delta f$ . The value of  $k$  is in the range from 0 and  $k_x/2$ , where  $k$  is the harmonic number.

By taking the Discrete Fourier Transform (DFT) of (3):

$$X_1(k) = \sum_k X_{1k}(k) \quad (5)$$

The discrete time signal (3) can be generated by the  $k_x$  point IDFT of (5):

$$x_1(n) = \text{IDFT} [X_1(k)] \quad (6)$$

It is easily seen that the 1<sup>th</sup> baud is generated by taking the IDFT of a complex valued array of length  $k_x$ . The values in the array,  $x_1(n)$  are the discrete time samples of the analog transmit signal. The generation of the 1<sup>th</sup> baud is completed by clocking the  $k_x$  samples out at  $f_x$  samples/sec. The entire packet is completed by an  $L$  fold repetition of the procedure.

## B. TRELLIS CODED MODULATION

Trellis coded modulation evolved as a combination of coding and modulation techniques for digital transmission over band limited channels. The primary advantage for using trellis coded modulation over other coding schemes is that significant coding gains can be achieved without compromising bandwidth efficiency [Ref 2:pp 5-12]. Trellis coded

modulation schemes employ redundant nonbinary modulation in combination with a finite-state encoder to govern the selection of modulation signals and to generate coded signal sequences. A simple four state scheme can improve the reception of a digital transmission by as much 3db in additive white gaussian noise. If more complex coding schemes are used gains of 6db or more may be achieved. In order to achieve the potential gains of a trellis coded signal a soft decision decoder, such as a Viterbi decoder, must be utilized in the receiver. These gains can also be achieved without reducing the information rate or increasing the bandwidth as required by conventional error correction schemes.

For low to medium data rates ( $\leq 4800$  bits/s), signaling methods that use independent symbol-by-symbol transmission are adequate to provide acceptably low error rates over voice grade circuits. When data rates increase in speed ( $\geq 9600$  bits/s) the same is not true, QAM and optimal signal sets fail to provide acceptably low error rates.[Ref 3:pp 648-649]

There are many factors which comprise linear and nonlinear distortion on a voiceband channel including phase jitter, frequency offset and additive noise. It was shown in that, relative to the uncoded system, trellis codes with four and eight states provide marked improvement in performance with respect to additive noise, second and third harmonic distortion, phase jitter, impulse noise and other channel impairments.[Ref 3:pp 649-651]

For an uncoded system the binary data transmit rate is equal to  $m/T$  bits/sec, where  $m$  is the number of bits/symbol and  $1/T$  the symbol rate. In a conventional QAM system (uncoded) there are  $2^n$  discrete symbol points (amplitude and/or phase levels) with each successive symbol transmitted



independently. The error performance depends on the minimum distance between the signal points (the larger the distance, the lower the error rate). The minimum distance at the transmitter is limited by the average power allowed on the circuit and the choice of the signal points. Even with the use of in-phase and quadrature components the minimum distance ( $d_{\min}$ ) between points decreases with the increase in the number of symbols,  $m$ , and constant average power. This results in a degradation at higher transmission rates assuming that there is a constant symbol rate.

The objective of coding is to increase the effective minimum distance between the signals without increasing the average power. One method of accomplishing this is with the use of convolutional encoder. In a convolutional encoder there are  $m$  current bits, and  $v$  past bits used to develop the codeword. The  $v$  past bits define the state of the encoder and are operated on to produce  $m+j$  bits, the rate of the code is described as  $m/m+j$ . The  $m+j$  bits require  $2^{m+j}$  discrete channel symbols. Using a convolutional encoder the minimum distance between symbols is no longer the measure of error performance, performance is now a measure of the minimum distance between the allowed transition of symbols from one state to another.[Ref 3:p 649] A convolutional encoder using a shift register to provide two past bits for a 2/3 rate convolutional code is shown in Figure 2. The allowed transition between states is shown in Figure 3. A convolutional code can be described as an  $(n,k,m)$  code, where  $n$  is the number of encoded bits,  $k$  the number of information bits and  $m$  the number of past bits used for encoding.

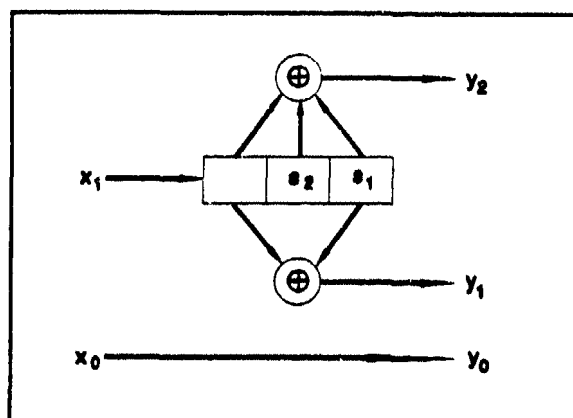


Figure 2 2/3 Rate Convolutional Encoder (from Ref 3:pp 651)

The input and output relationship are depicted by the branches on the trellis diagram. The upper branch depicts the transition with  $x_0$  set to "0", the lower branch depicts the transition with  $x_0$  set to "1". Each node of the trellis diagram represents one of four states created by the past bits  $s_1$  and  $s_2$ .

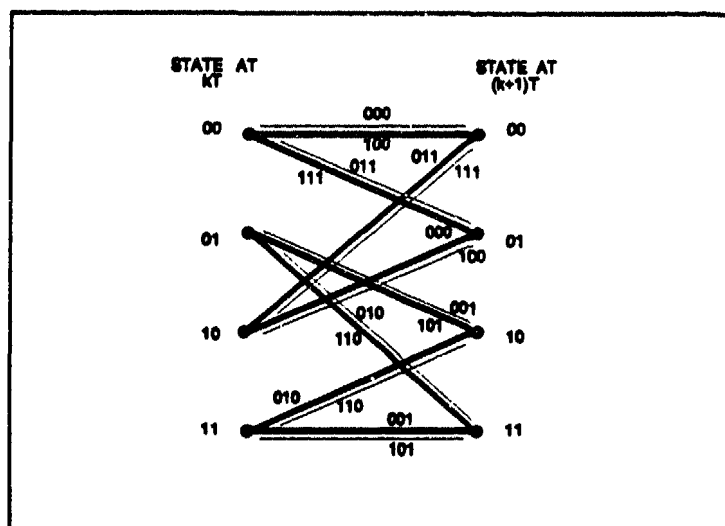


Figure 3 Trellis for 2/3 rate convolutional code.(from Ref 3:pp 651)

In order to achieve the optimum decoding gains from the use of convolutional encoders the decoder must use a trace back routine to find

the most probable path through the trellis. The rules for bit to symbol mapping for coded systems:[Ref 3:pp 650]

1. All parallel transitions in the trellis structure receive maximum possible Euclidean distance in the signal constellation.

2. All transitions diverging from a merging into a trellis state receive maximum possible Euclidean distance.

### C. VITERBI DECODER

The Viterbi decoder utilizes a maximum likelihood sequence estimation method to decode the incoming data stream. A predetermined measure is used to determine the symbol sequence which is closest to the received symbol sequence. At any time,  $k$ , the shortest path, called the survivor, entering each state (node) of the trellis is retained. To proceed to time  $k+1$ , all time  $k$  survivors are extended by computing the metrics (lengths) of the extended path segments based on the calculated branch metrics, dependent on the branch symbols in the trellis and the value of the received sample.[Ref 3:pp 648-649] An example of a trellis and a path through the trellis is shown in Figure 4. The metrics of the remaining paths are computed and the shortest path retained. The shortest length into each state, the  $(k+1)$  survivor is retained. The number of survivors never exceeds the number of states in the trellis.

The basic operations required in a soft decision Viterbi decoder are:[Ref 3:p 651]

- computation of branch metrics, for an additive white gaussian noise channel, are proportional to  $(r-x_i)^2$  where  $r$  is the received sample and  $x_i$  is the noise free symbol associated with the message.
- addition of branch metrics and survivors to determine the survivors for each state.

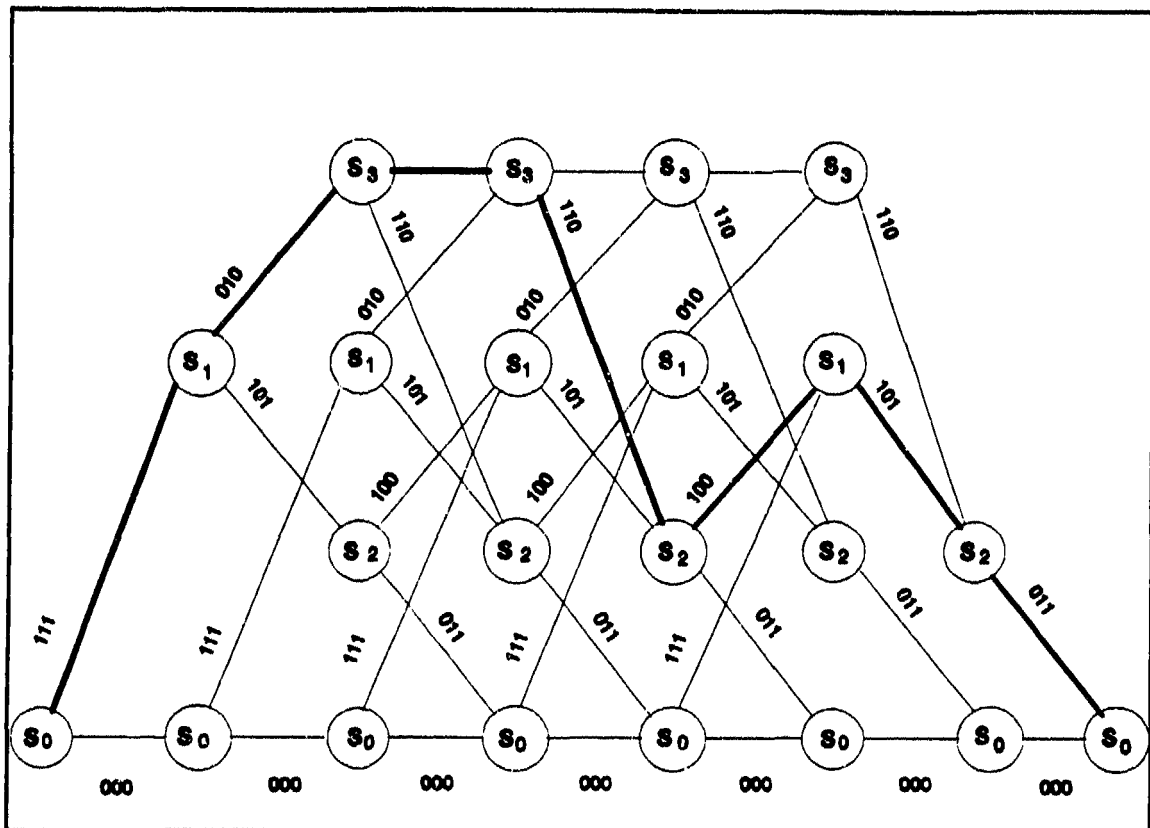


Figure 4 Trellis diagram for a (3,1,2) code. (from Ref 4:p 316)

- comparison along the extended path metrics to determine the survivor for each state.

It was shown that the Viterbi algorithm was equivalent to a dynamic programming solution to the problem of finding the shortest path through a weighted graph [Ref 3:pp 317-321]. The decoder must produce an estimate  $\hat{v}$  of the codeword  $v$  based on the received sequence  $r$ . For an information sequence of length  $L$ , the trellis must contain  $L+m+1$  levels or time units to decode the sequence. An  $(n,k,m)$  code has an information sequence of length  $Kl$ , and is encoded into a codeword of length  $N=n(L+m)$ . A maximum likelihood decoder (MLD) for a discrete memoryless channel (DMC) chooses

$\hat{v}$  as the codeword  $v$  which maximizes the log-likelihood function  $\log P(r|v)$ . Since for a DMC:

$$P(\mathbf{r} | \mathbf{v}) = \prod_{i=0}^{L \cdot m - 1} P(\mathbf{r}_i | \mathbf{v}_i) = \prod_{i=0}^{N-1} P(r_i | v_i) \quad (7)$$

it follows that log-likelihood function is formed by the summation of the branch metrics:

$$\log P(\mathbf{r} | \mathbf{v}) = \sum_{i=0}^{L \cdot m - 1} \log P(\mathbf{r}_i | \mathbf{v}_i) = \sum_{i=0}^{N-1} \log P(r_i | v_i) \quad (8)$$

where  $P(r_i | v_i)$  is a channel transition probability. This is a minimum error probability decoding rule when all code words are equally likely. The log-likelihood function  $\log P(\mathbf{r} | \mathbf{v})$  are called the metric of path  $v$  and is denoted  $M(\mathbf{r} | \mathbf{v})$ . A partial path metric is formed by summing up the partial path metrics for  $j$  branches and is expressed by:

$$M([\mathbf{r} | \mathbf{v}]_j) = \sum_{i=0}^{j-1} M(\mathbf{r}_i | \mathbf{v}_i) \quad (9)$$

The final survivor  $\hat{v}$  in the Viterbi algorithm is the maximum likelihood path;

$$M(\mathbf{r} | \hat{v}) \geq M(\mathbf{r} | v), \quad \text{all } v \neq \hat{v} \quad (10)$$

The path is then traced back to determine the symbol transmitted.[Ref. 4:pp 316-318]

### III. SYSTEM DEVELOPMENT

All the programs used in this thesis were run on an Ariel PC-56 DSP board. The PC-56 DSP board is an eight bit card that can be used in any industry standard computer. The primary components of the PC-56 are a 20 Mhz Motorola DSP 56001, 16k of external memory, a 24 bit bidirectional interrupt-driven port with a header for external I/O, a TLC32040 14 bit analog interface chip with built in input and output filters gain section. An Ariel PC-56D was also used for comparison, it contains a 27 Mhz Motorola DSP 56001, 64k of external memory and a NEXT compatible DB-15 port. For actual implementation of this system a DSP board with dual A/D and D/A converters is required.

The structure of the Motorola DSP 56001 makes it ideally suited for high speed communications. In the DSP chip there are 256 locations of 24 bit x and y memory that occupy the lowest 256 locations of the DSP address space. The locations from 256-511 are allocated for the on-chip ROM. The onboard ROM contains Mu-law and A-law expansion tables as well as a full four quadrant sine table. There are 512 locations of 24 bit high speed program RAM (PRAM) on the chip.[Ref 5]

A feature that makes the DSP 56001 desirable for use in this system is that it offers several addressing modes. It implements three types of arithmetic for addressing, linear, modulo and reverse carry. For each of the address registers R0-R7 there is an offset register N0-N7 and a modifier register M0-M7. The offset register contains the values to increment and decrement the address register. The modifier register

defines the type of address arithmetic to be used. For modulo arithmetic the contents of the modifier register Mn specify the base modulus.[Ref 6:pp 5-2,5-4] The DSP 56001 also provides three different addressing modes, register direct, address register indirect, and post or pre increment/decrement.

The basic configuration of an MFM transmitter and receiver are shown in Figure 5 and Figure 6. For the purpose of this project three types of modulators were used in the investigation for use on a DSP board. In previous systems implemented at NPS [Ref 1] and [Ref 7] the complex conjugate of the input data was loaded into the image frequencies of the IFFT. This resulted in only real data being generated by the IFFT. For this project complex data was loaded into all available locations to generate both real and complex data. The signal may be modulated using any type of modulation scheme. For the purpose of this thesis the three different modulators used a 16 QAM signal, a 2/3 rate convolutional encoder with an eight PSK signal and a 4/5 rate code with a 32 QAM signal using the CCITT modem standard V.32 convolutional encoder. The source code for the V.32 encoder and Viterbi decoder was included in an example manual from Motorola [Ref 8:pp A1-C2] for use on their simulator and was modified for use on the Ariel board to generate a Multi-Frequency Modulated signal.

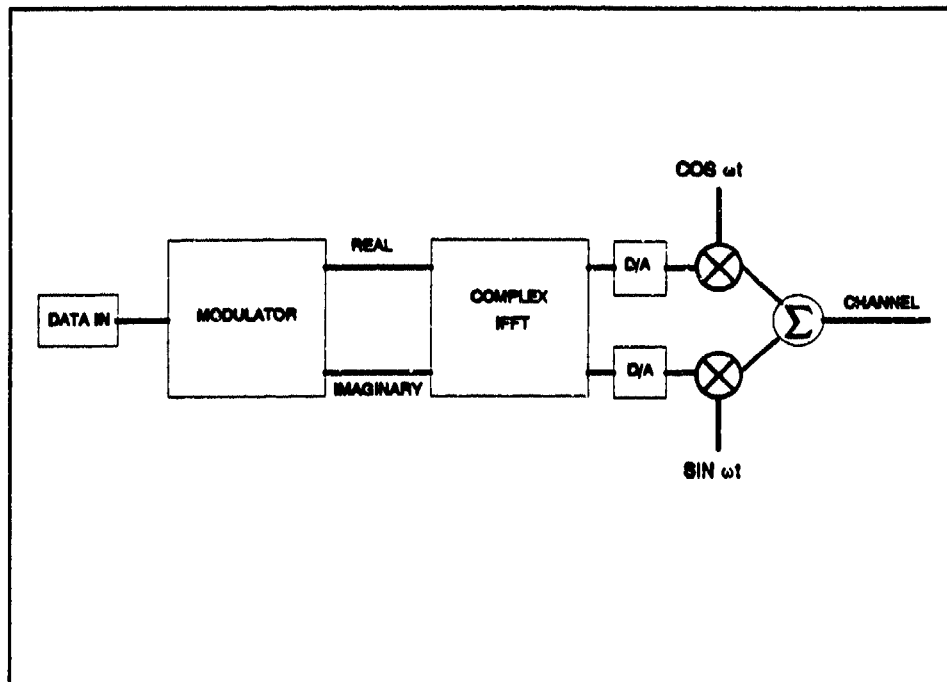


Figure 5 MFM Transmitter

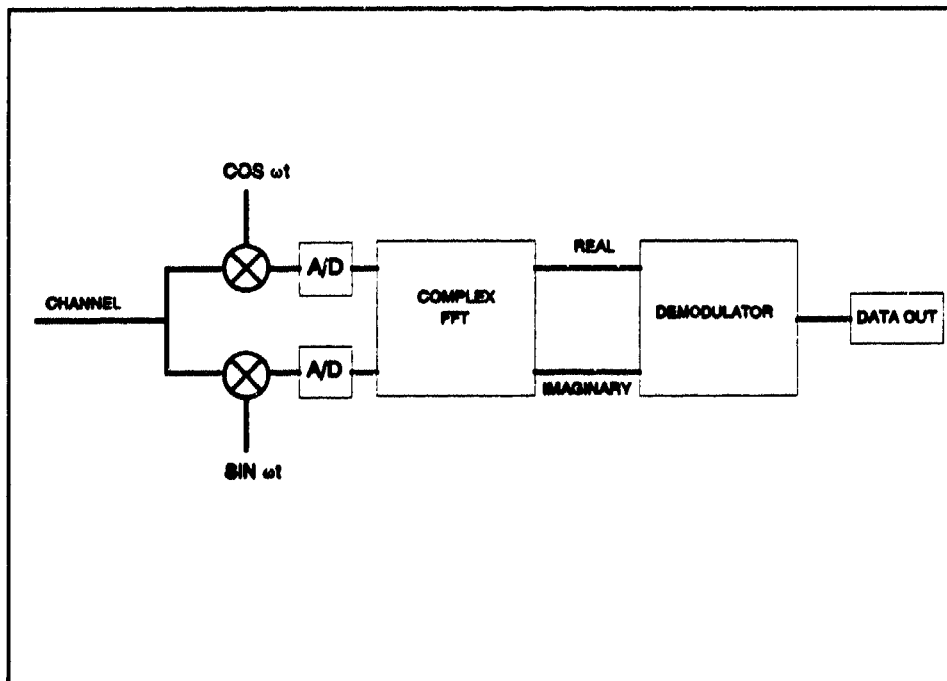


Figure 6 MFM Receiver



## A. ENCODERS

Of the 256 bins available in the IFFT array, only 201 message symbols are carried in each baud. The other 55 bins are loaded with zeros to allow for filtering of the signal. Once the 256 bins are filled, the IFFT subroutine is called to generate the values for the MFM signal. At this point the values would be clocked out through the D/A converters.

### 1. 16 QAM Encoder

At initialization of the system the message to be transmitted is downloaded from the host computer as well as the programs for encoding (QAM16EN) the signal and the data for the look-up table (16QAMRE.DAT and 16QAMIM.DAT). The data is read in using four bit increments. The value read in is moved into an offset register and used to determine the coordinates of the points on the constellation in Figure 7. The real values of the constellation are stored in the x memory and the corresponding imaginary values are stored in the y memory. Once the constellation values are determined the real and complex values are stored in memory. Once one hundred samples have been read into memory the routine installs 55 zeros at the center of the array then reads the remainder of the 256 symbols. Once all 256 samples are stored the IFFT routine is called to generate the time domain signal.

### 2. 2/3 Rate Convolutional Encoder

At initialization of the system the message to be sent as well as the encoder (23ENCOD) and the data files (23REAL.DAT and 23IMAG.DAT) are loaded into memory. In the 2/3 rate encoder two bits are read in from the input message and using the convolutional encoder of Figure 2 a third bit

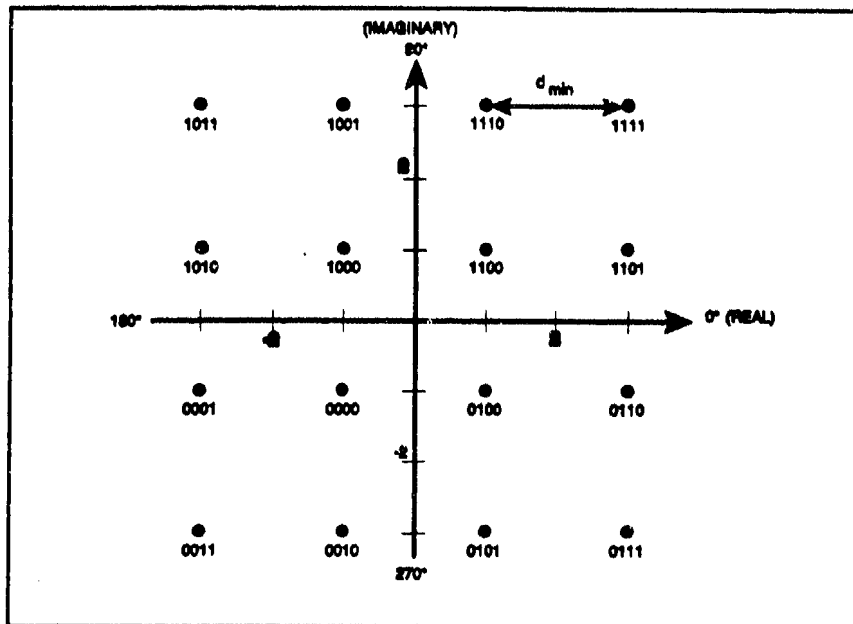


Figure 7 CONSTELLATION FOR 16QAM SIGNAL (from Ref.8:p 2-2)

is generated. The eight PSK constellation in Figure 8 is used to transmit the message. A look up table is used to find the points on the constellation. After the points on the constellation are found, the real

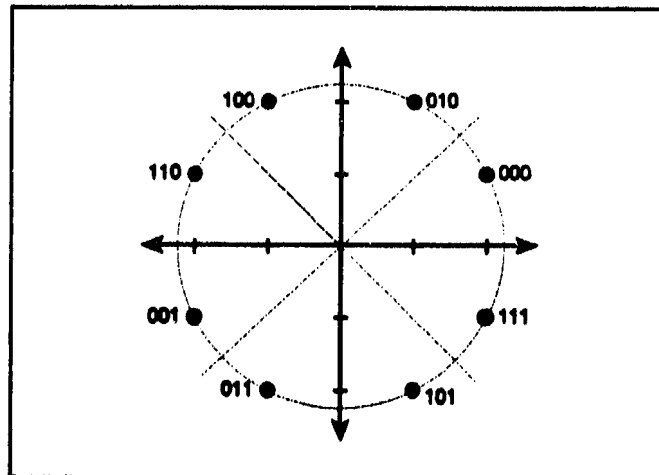


Figure 8 2/3 Rate Code Constellation

and imaginary values are loaded into an array. After the first 100 samples are loaded into the array, 55 zeros are loaded into the array to allow for filtering and the remainder of symbols are read. Once all 256 values are loaded the IFFT is performed and the values are stored ready to be clocked out.

### 3. V.32 Convolutional Encoder

At initialization the message, encoder program (MFMECOD) and data files (QAMREAL.DAT and QAMIMAG.DAT) are downloaded to the to the DSP board. For the V.32 encoder after the four bit symbol is read, the convolutional encoder Figure 9 is used to generate a fifth redundant bit.

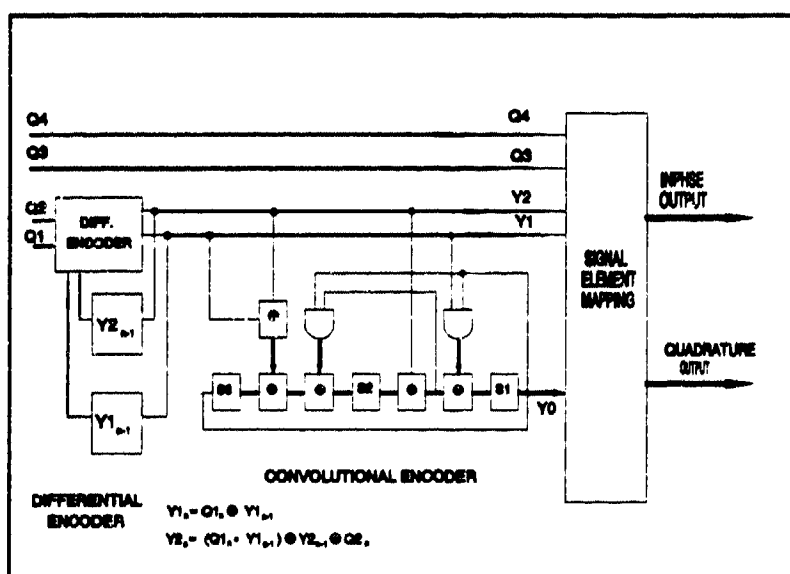


Figure 9 V.32 Convolutional Encoder (from Ref. 8:p 2-4)

The 32 QAM constellation in Figure 10 is used for the five bit signal. A look up table is used to determine the real and imaginary values for the corresponding point on the constellation. As in the 16 QAM encoder and

the 2/3 rate code encoder, 201 encoded symbols and 55 zeros are loaded into the IFFT array and the IFFT is performed.

#### B. GENERATING THE MFM SIGNAL

When all 256 bins have been loaded the program calls the routine to perform the IFFT. The routine used to perform the IFFT was generated by using the relationship  $x(n) = (FFT[X^t(k)])^t / N$ . The program to generate the FFT was included with the Ariel DSP package<sup>1</sup>. In order to speed up

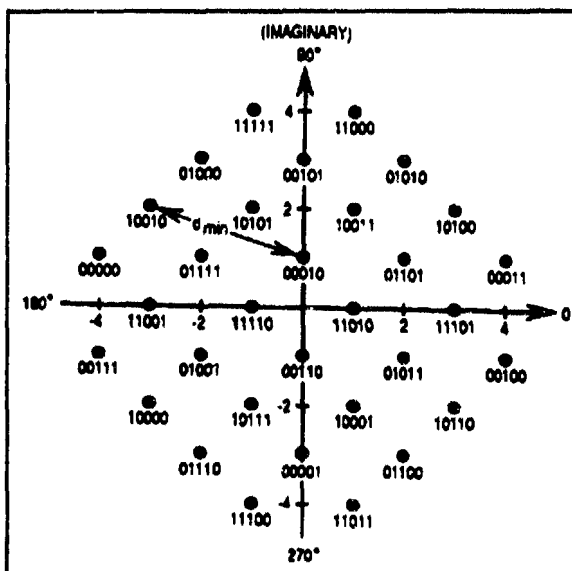


Figure 10 32 QAM Constellation  
(from Ref. 8:p 2-3)

<sup>1</sup>Unless otherwise specified, all software (C) COPYRIGHT 1989 by Ariel Corporation, Highland Park, NJ. All rights reserved. You may use the software provided by Ariel Corporation on any one computer; copy the object code into any machine readable form for your use. You may modify the software provided by Ariel and/or merge or incorporate it into any general use software program of your development except for a program of similar nature to the Ariel product. You may freely reproduce any such program of your development; however the merged or incorporated part of the Ariel provided software will continue to be subject to all other provisions of this agreement.

the routine as much as possible the values used in the look up table were conjugated and scaled by 256 to save from doing them in the modulator. By using the prescaled and conjugated values in the encoder constellations the IFFT routines require no more time than the FFT routine used in the decoder.

After computing the IFFT the real and complex values are stored in memory. By utilizing a DSP board with dual D/A converters the real and imaginary values can be clocked out at the sampling frequency  $f_x$ . The design of the system may be altered to either allow transmission of each 256 symbol packet or store the entire message and transmit at the end of the message.

### C. DECODERS

After using a quadrature receiver to recover the inphase and quadrature components, the signals are sampled at the same frequency,  $f_x$ , as used in the encoder. These sampled values are used to determine the transmitted symbols.

#### 1. 16 QAM DECODER

At initialization the boundary data file BOUN16.D and the decoder program QAM16DEC must be loaded onto the DSP board. To decode the 16 QAM signal the constellation was partitioned as shown in Figure 11. The magnitude of each received signal value is compared to the boundaries in the first quadrant. Once a bounded area is found the actual values are then used to determine the correct quadrant. The data file BOUN16.D is indexed and the corresponding symbol is read out.

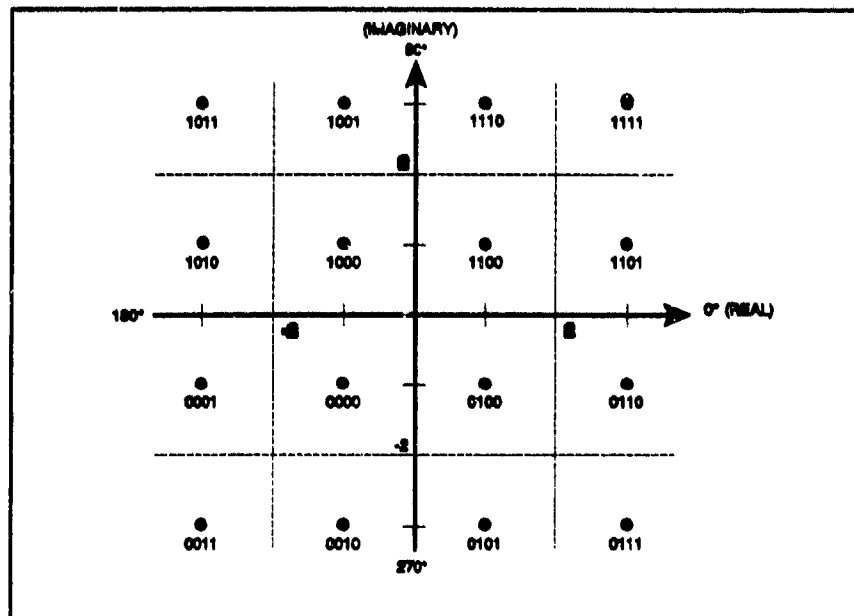


Figure 11 PARTITIONED 16 QAM CONSTELLATION

## 2. 2/3 Rate Code Decoder

The use of a convolutional encoder requires the use of a soft decoder such as a Viterbi Decoder to recover the transmitted symbol. The boundary data file BOUN23.D and the Viterbi decoder program MFM23DEC are first loaded into memory and run. After computing the FFT to recover the transmitted symbols, a received point is read out of the array and the quadrant of the constellation (Figure 8) that it lies in is found. The data file BOUN23.D holds the four closest points, one in each state, to the quadrant that the received point lies in. A boundary file is used to help speed up the decoder routine, instead of computing the distance to all points in the constellation only the point closest in each state is used for computing the euclidean distance to the received point. Using the

received point and the four values found in BOUN23.D the euclidean distance to each point is computed. The accumulated distance table is updated with the distance to each state. The smallest accumulated distance is found and the trellis is traced back 16 time periods to find the most likely transmitted point. After finding the most likely point it must be decoded. The bit Y2 is discarded and using the relation  $Y1 = X1 \oplus S1$  the value of X1 is recovered by using past state information and  $X1 = Y1 \oplus S1$ . The value of Y0 is output as X0. The values are stored in memory.

### 3. V.32 DECODER

The use of a convolutional encoder in the V.32 system requires that a Viterbi Decoder must also be used to recover the transmitted symbol. The boundary file BOUND.D and the program file MFMDECOD are first loaded into memory. The constellation must first be partitioned in such a way that the partition equally divides the distance between the four symbols in the same state. The partition used for the state 110 is shown in Figure 12. By using this method the partitions for all eight states may be imposed on the constellation resulting in 52 separate partitions as shown in Figure 13. For each partition there are eight points, one from each state, that is closest to the boundary. These eight points for each of the 52 boundaries are stored in the data file BOUND.D that is loaded into the processor at initialization. Once a bounded area has been found, the eight points are used to determine the euclidean distance from the received point to the points read from BOUND.D. The distances calculated

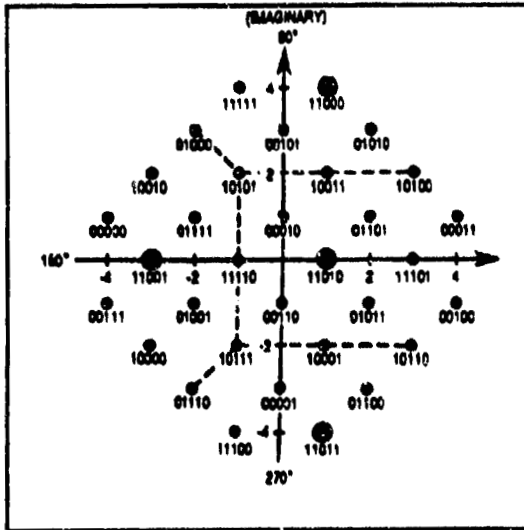


Figure 12 32 QAM Constellation (from Ref. 8: p 3-7)

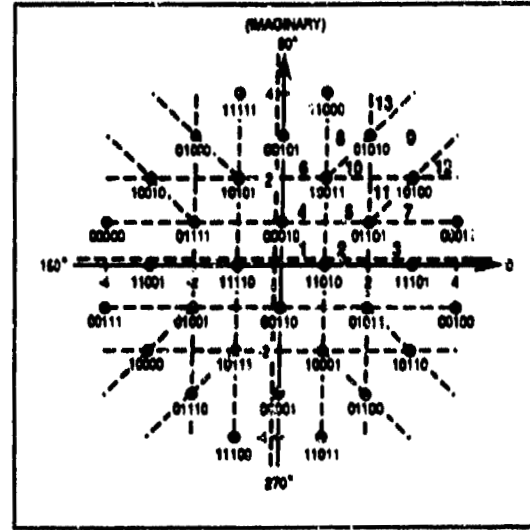


Figure 13 Partitioned 32 QAM Constellation (from Ref. 8: p 3-7)

are used to update the accumulated distance to each state. The state with the smallest accumulated distance is found and the trellis is traced back 16 time periods to find the input state at the end of the most likely path. The closest point in that state to the input point at that time period is found and output. The most significant bit is masked off. The differential encoding used on the two most significant bits must be decoded by:

$$Q1_n = Y1_n \oplus Y1_{n-1} \quad (11)$$

$$Q2_n = (Q1_n \cdot Y1_{n-1}) \oplus Y2_{2n-1} \oplus Y2_n \quad (12)$$

Once the two most significant bits have been decoded the symbol is output to memory.



#### IV. SYSTEM OPERATION

The Digital Signal Processing boards used to run the programs that were developed did not have dual D/A, A/D converters required to fully implement an MFM system. The programs as listed, do not fully implement a MFM system. There are no subroutines included for the clocking out of samples through D/A converters in the encoders and no sampling routines in the decoders. The encoding programs read in the data to be transmitted from memory, encode the data and store the values created by the IFFT in memory. The same locations are used to store all values generated, it is assumed that the values will be clocked out once available freeing up these locations for the next baud. The values would be clocked out through the D/A converters to generate a signal. In the decoder programs, the data is read out of locations where the sampled values would be stored. The same locations are used for all sampled values, it is assumed each baud will be decoded prior to receiving the next baud. If a convolutional encoder is used, a decision must be made as to whether the next baud should be delayed to allow decoding of the previous baud, or transmit the baud when available and store the values in the decoder for off line decoding.

Once the modulation technique is chosen the appropriate constellation data files must be loaded for the look up tables used in the decoder. These files are located in Appendices D, H, L. Once the appropriate data files are loaded the encoder program and message file are loaded into memory and the encoder is run. The programs developed were run out of

Ariel's BUG-56 monitor-debugger, they can also be adapted to run as subroutines in a Microsoft C program. The monitor-debugger allowed easy access to all the chips registers and functions making running and debugging the programs simpler.

To use the decoder the appropriate boundary values must be loaded. Once the boundary values are loaded the decoder program is loaded and run. The output is stored in memory.

All of the programs listed are written in assembly language for the DSP 56001 and must be compiled into a loadable file using the Motorola assembler. All of the data files are properly formatted to be read into the correct memory locations. If the programs are run out of the BUG-56 monitor-debugger, a macro can be created to load all the files needed for an encoder or decoder using one instruction.

## V. CONCLUSIONS

The time required for the encoder/decoder for a 256 sample baud is shown in Table I. The Turbo Pascal routine used in past projects

**Table I Sample Times for Programs Using 256 Sample Baud**

PROGRAMS	TIME(ms)	
	20 Mhz 56001	27 Mhz 56001
4096 pt complex fft	.023 sec	.017 sec
256 pt complex fft	1	.7
MFM PROGRAMS (for 256 sample baud)		
16 QAM Encoder	2.7	2.0
16 QAM Decoder	2.7	2.0
2/3 convolutional encoder	3.2	2.4
2/3 rate code Viterbi decoder	10.8	8.0
V.32 encoder (w/o diff enc)	3.6	2.7
V.32 Viterbi decoder (w/o diff enc)	15.8	11.7
V.32 encoder	3.7	2.8
V.32 Viterbi decoder	16.9	12.5

required 22 seconds to perform a 4096 point complex FFT on an 8 Mhz AT computer with a coprocessor.[Ref. 9:p 18] It is readily apparent that the Digital Signal Processor has a tremendous performance advantage over normal software routine. Using Matlab benchmarks a Sun Sparc station required .34 seconds and a 20 Mhz 386 with a coprocessor required 1.16 seconds for a 4096 point complex FFT.

Multi-Frequency Modulation can be easily implemented on a Digital Signal Processor Board. The programs for implementing the 16 QAM system required the same amount of time to encode and to decode. There is little penalty for using a trellis encoder but the Viterbi decoder takes over three times longer than the encoder for the 2/3 rate code and almost four times as long for the V.32 decoder.

The use of DSP boards in implementing MFM shows much improvement over existing techniques. Suggestions for future research include running the MFM programs on DSP boards with the required dual D/A, A/D converters. A determination must be made as to whether the decoder should store the entire message or delay transmission of a baud until the previous baud is decoded. Another alternative is to use more than one processor, one to encode/decode and another to clock out/sample the data.

The versatility and speed of Digital Signal Processors make them ideally suited for use for a Multi-Frequency Modulated System. They offer much greater performance than is currently available using software routines and are can easily perform other functions by simply loading a new program. The continuing development of more DSP compatible products show that there will be greater uses of DSP technology in the future.

## APPENDIX A. FFT

```

;
; This program originally available on the Motorola DSP bulletin board.
; It is provided under a DISCLAIMER OF WARRANTY available from
; Motorola DSP Operation, 6501 Wm. Cannon Drive W., Austin, Tx., 78735.
;
; Radix 2, In-Place, Decimation-In-Time FFT (fast).
;
; Last Update 18 Aug 88   Version 1.0
;
fft macro  points,data,odata,coef
fft ident  1,0
;
; Radix 2 Decimation in Time In-Place Fast Fourier Transform Routine
;
;      Complex input and output data
;      Real data in X memory
;      Imaginary data in Y memory
;      Normally ordered input data
;      Normally ordered output data
;      Coefficient lookup table
;      -Cosine values in X memory
;      -Sine values in Y memory
;
; Macro Call - fft  points,data,odata,coef
;
;      points      number of points (16-32768, power of 2)
;      data        start of data buffer
;      odata       start of output data buffer
;      coef        start of sine/cosine table
;
; Alters Data ALU Registers
;      x1      x0      y1      y0
;      a2      a1      a0      a
;      b2      b1      b0      b
;
; Alters Address Registers
;      r0      n0      m0
;      r1      n1      m1
;      n2
;
;      r4      n4      m4
;      r5      n5      m5
;      r6      n6      m6
;

```

```

; Alters Program Control Registers
;     pc     sr
;
; Uses 6 locations on System Stack
;
; Latest Revision - 18 Aug-88
;

    move #data,r0           ;initialize input pointer
    move #points/4,n0       ;initialize input and output pointers offset
    move n0,n4              ;
    move n0,n6              ;initialize coefficient offset
    move #points-1,m0       ;initialize address modifiers
    move m0,m1              ;for modulo addressing
    move m0,m4
    move m0,m5

;
; Do first and second Radix 2 FFT passes, combined as 4-point butterflies
;
    move          x:(r0)+n0,x0
    tfr x0,a      x:(r0)+n0,y1

    do n0,_twopass
    tfr y1,b      x:(r0)+n0,y0
    add y0,a      x:(r0),x1           ;ar+cr
    add x1,b      r0,r4              ;br+dr
    add a,b      (r0)+n0             ;ar'=(ar+cr)+(br+dr)
    subl b,a      b,x:(r0)+n0        ;br'=(ar+cr)-(br+dr)
    tfr x0,a      ,x0                y:(r0),b
    sub y0,a      x0,x:(r0)          y:(r4)+n4,y0 ;ar-cr
    sub y0,b      x0,x:(r0)          ;bi-di
    add a,b      y:(r0)+n0,x0        ;cr'=(ar-cr)+(bi-di)
    subl b,a      b,x:(r0)          ;dr'=(ar-cr)-(bi-di)
    tfr x0,a      ,x0                y:(r4),b
    add y0,a      x0,x:(r0)+n0        y:(r0)+n0,y0 ;bi+di
    add y0,b      x0,x:(r0)+n0        ;ai+ci
    add b,a      y:(r0)+,x0          ;ai'=(ai+ci)+(bi+di)
    subl a,b      a,y:(r4)+n4        ;bi'=(ai+ci)-(bi+di)
    tfr x0,a      b,y:(r4)+n4
    sub y0,a      x1,b              ;ai-ci
    sub y1,b      x:(r0)+n0,x0      ;dr-br
    add a,b      x:(r0)+n0,y1        ;ci'=(ai-ci)+(dr-br)
    subl b,a      b,y:(r4)+n4        ;di'=(ai-ci)-(dr-br)
    tfr x0,a      ,y:(r4)+

    _twopass
;
; Perform all next FFT passes except last pass with triple nested DO loop
;
    move #points/8,n1       ;initialize butterflies per group
    move #4,n2              ;initialize groups per pass
    move #-1,m2             ;linear addressing for r2

```

```

        move #0,m6                ;initialize C address modifier for
                                   ;reverse carry (bit-reversed) addressing

        do #@cvi(@log(points)/@log(2)-2.5),_end_pass    ;example: 7 passes
for 1024 pt. FFT
        move #data,r0                ;initialize A input
pointer
        move r0,r1
        move n1,r2
        move r0,r4                ;initialize A
output pointer
        move (r1)+n1                ;initialize B input
pointer
        move r1,r5                ;initialize B
output pointer
        move #coef,r6                ;initialize C input
pointer
        lua (r2)+,n0                ;initialize pointer
offsets
        move n0,n4
        move n0,n5
        move (r2)-                ;butterfly loop
count
        move          x:(r1),x1      y:(r6),y0                ;lookup -sine and
-cosine values
        move          x:(r6)+n6,x0    y:(r0),b                ;update C pointer,
preload data
        mac x1,y0,b          y:(r1)+,y1
        macr -x0,y1,b        y:(r0),a

        do n2,_end_grp
        do r2,_end_bfy
        subl b,a          x:(r0),b          ,y:(r4)                ;Radix 2 DIT
butterfly kernel
        mac -x1,x0,b    x:(r0)+,a          ,y:(r5)
        macr -y1,y0,b    x:(r1),x1
        subl b,a          b,x:(r4)+          y:(r0),b
        mac x1,y0,b          y:(r1)+,y1
        macr -x0,y1,b    a,x:(r5)+          y:(r0),a
_end_bfy
        move (r1)+n1
        subl b,a          x:(r0),b          ,y:(r4)
        mac -x1,x0,b    x:(r0)+n0,a          ,y:(r5)
        macr -y1,y0,b    x:(r1),x1          y:(r6),y0
        subl b,a          b,x:(r4)+n4          y:(r0),b
        mac x1,y0,b    x:(r6)+n6,x0          y:(r1)+,y1
        macr -x0,y1,b    a,x:(r5)+n5          y:(r0),a
_end_grp
        move n1,b1
        lsr b    n2,a1          ;divide butterflies per group by two
        lsl a    b1,n1          ;multiply groups per pass by two

```

```

        move a1,n2
_end_pass
;
; Do last FFT pass
;
        move #2,n0          ;initialize pointer offsets
        move n0,n1
        move #points/4,n4    ;output pointer A offset
        move n4,n5          ;output pointer B offset
        move #data,r0        ;initialize A input pointer
        move #odata,r4       ;initialize A output pointer
        move r4,r2           ;save A output pointer
        lua (r0)+,r1         ;initialize B input pointer
        lua (r2)+n2,r5       ;initialize B output pointer
        move #0,m4           ;bit-reversed addressing for output ptr. A
        move m4,m5           ;bit-reversed addressing for output ptr. B
        move #coef,r6        ;initialize C input pointer
        move (r5)-n5         ;predecrement output pointer
        move          x:(r1),x1      y:(r6),y0
        move          x:(r5),a       y:(r0),b

        do n2,_lastpass
        mac x1,y0,b x:(r6)+n6,x0 y:(r1)+n1,y1 ;Radix 2 DIT butterfly
kernel
        macr -x0,y1,b a,x:(r5)+n5 y:(r0),a ;with one butterfly per
group
        subl b,a x:(r0),b b,y:(r4)
        mac -x1,x0,b x:(r0)+n0,a a,y:(r5)
        macr -y1,y0,b x:(r1),x1 y:(r6),y0
        subl b,a b,x:(r4)+n4 y:(r0),b
_lastpass
        move          a,x:(r5)+n5
        endm

```



## APPENDIX B. IFFT

```

; This program uses the same routine used in the program FFT. The IFFT is
; calculated using the relationship  $IFFT = (FFT[X(k)]/N)$ . It is assumed that
; the values used in the constellation are conjugated and prescaled by N.
; If the values to be used are not conjugated a routine must be added to
; the beginning of this routine to conjugate the values. The division by
; N can also be accomplished by using left shifts, but will slow down the
; program.
;
; Radix 2, In-Place, Decimation-In-Time IFFT (fast).
;
;
; ifft    macro    points,data,odata,coef
; ifft    ident    1,0
;
; Radix 2 Decimation in Time In-Place Inverse Fast Fourier Transform
; Routine
;
;         Complex input and output data
;         Real data in X memory
;         Conjugated and prescaled imaginary data in Y memory
;         Normally ordered input data
;         Normally ordered output data
;         Coefficient lookup table
;         -Cosine values in X memory
;         -Sine values in Y memory
;
; Macro Call - ifft    points,data,odata,coef
;
;         points    number of points (16-32768, power of 2)
;         data      start of data buffer
;         odata     start of output data buffer
;         coef      start of sine/cosine table
;
; Alters Data ALU Registers
;         x1        x0        y1        y0
;         a2        a1        a0        a
;         b2        b1        b0        b
;
; Alters Address Registers
;         r0        n0        m0
;         r1        n1        m1
;                 n2
;
;         r4        n4        m4
;         r5        n5        m5

```

```

;      r6      n6      m6
;
; Alters Program Control Registers
;      pc      sr
;
; Uses 6 locations on System Stack
;
; Latest Revision - 18 Aug-88
;
;      move #data,r0          ;initialize input pointer
;      move #points/4,n0      ;initialize input and output pointers offset
;      move n0,n4              ;
;      move n0,n6              ;initialize coefficient offset
;      move #points-1,m0      ;initialize address modifiers
;      move m0,m1              ;for modulo addressing
;      move m0,m4
;      move m0,m5
;
; Do first and second Radix 2 IFFT passes, combined as 4-point butterflies
;
;      move          x:(r0)+n0,x0
;      tfr x0,a       x:(r0)+n0,y1
;
;      do n0,_twopass
;      tfr y1,b       x:(r0)+n0,y0
;      add y0,a        x:(r0),x1          ;ar+cr
;      add x1,b        r0,r4              ;br+dr
;      add a,b         (r0)+n0            ;ar'=(ar+cr)+(br+dr)
;      subl b,a        b,x:(r0)+n0        ;br'=(ar+cr)-(br+dr)
;      tfr x0,a        a,x0               y:(r0),b
;      sub y0,a         x0,x:(r0)          y:(r4)+n4,y0 ;ar-cr
;      add a,b          y:(r0)+n0,x0       ;bi-di
;      subl b,a         b,x:(r0)           ;cr'=(ar-cr)+(bi-di)
;      tfr x0,a        a,x0               y:(r4),b       ;dr'=(ar-cr)-(bi-di)
;      add y0,a         x0,x:(r0)+n0       y:(r0)+n0,y0 ;bi+di
;      add y0,b         x0,x:(r0)+n0       ;ai+ci
;      add b,a          y:(r0)+,x0         ;ai'=(ai+ci)+(bi+di)
;      subl a,b         a,y:(r4)+n4       ;bi'=(ai+ci)-(bi+di)
;      tfr x0,a        b,y:(r4)+n4
;      sub y0,a        x1,b               ;ai-ci
;      sub y1,b        x:(r0)+n0,x0       ;dr-br
;      add a,b          x:(r0)+n0,y1       ;ci'=(ai-ci)+(dr-br)
;      subl b,a        b,y:(r4)+n4       ;di'=(ai-ci)-(dr-br)
;      tfr x0,a        a,y:(r4)+
;      _twopass
;
; Perform all next IFFT passes except last pass with triple nested DO loop
;

```

```

    move #points/8,n1      ;initialize butterflies per group
    move #4,n2             ;initialize groups per pass
    move #-1,m2            ;linear addressing for r2
    move #0,m6             ;initialize C address modifier for
                           ;reverse carry (bit-reversed) addressing

    do #@cvi(@log(points)/@log(2)-2.5),_end_pass    ;example: 7 passes
for 1024 pt. IFFT
    move #data,r0      ;initialize A input
pointer
    move r0,r1
    move n1,r2
    move r0,r4      ;initialize A output
pointer
    move (r1)+n1      ;initialize B input
pointer
    move r1,r5      ;initialize B output
pointer
    move #coef,r6      ;initialize C input
pointer
    lua (r2)+,n0      ;initialize pointer
offsets
    move n0,n4
    move n0,n5
    move (r2)-
    move          x:(r1),x1      y:(r6),y0      ;butterfly loop count
values          x:(r6)+n6,x0      y:(r0),b      ;lookup -sine and -cosine
    move          x:(r6)+n6,x0      y:(r0),b      ;update C pointer, preload
data
    mac x1,y0,b          y:(r1)+,y1
    macr -x0,y1,b          y:(r0),a

    do n2,_end_grp
    do r2,_end_bfy
    subl b,a          x:(r0),b          b,y:(r4)      ;Radix 2 DIT butterfly
kernel
    mac -x1,x0,b      x:(r0)+,a          a,y:(r5)
    macr -y1,y0,b      x:(r1),x1
    subl b,a          b,x:(r4)+          y:(r0),b
    mac x1,y0,b          y:(r1)+,y1
    macr -x0,y1,b      a,x:(r5)+          y:(r0),a
_end_bfy
    move (r1)+n1
    subl b,a          x:(r0),b          b,y:(r4)
    mac -x1,x0,b      x:(r0)+n0,a          a,y:(r5)
    macr -y1,y0,b      x:(r1),x1          y:(r6),y0
    subl b,a          b,x:(r4)+n4          y:(r0),b
    mac x1,y0,b      x:(r6)+n6,x0          y:(r1)+,y1
    macr -x0,y1,b      a,x:(r5)+n5          y:(r0),a
_end_grp
    move n1,b1

```

```

        lsr b    n2,a1      ;divide butterflies per group by two
        lsl a    b1,n1      ;multiply groups per pass by two
        move a1,n2
    _end_pass
;
; Do last IFFT pass
;
        move #2,n0          ;initialize pointer offsets
        move n0,n1
        move #points/4,n4    ;output pointer A offset
        move n4,n5          ;output pointer B offset
        move #data,r0        ;initialize A input pointer
        move #odata,r4       ;initialize A output pointer
        move r4,r2          ;save A output pointer
        lua (r0)+,r1         ;initialize B input pointer
        lua (r2)+n2,r5       ;initialize B output pointer
        move #0,m4          ;bit-reversed addressing for output ptr. A
        move m4,m5          ;bit-reversed addressing for output ptr. B
        move #coef,r6        ;initialize C input pointer
        move (r5)-n5        ;predecrement output pointer
        move          x:(r1),x1      y:(r6),y0
        move          x:(r5),a       y:(r0),b

        do n2,_lastpass
        mac x1,y0,b    x:(r6)+n6,x0    y:(r1)+n1,y1    ;Radix 2 DIT butterfly
kernel
        macr -x0,y1,b  a,x:(r5)+n5    y:(r0),a          ;with one butterfly per
group
        subl b,a
                                ;complete last butterfly
        neg b                                ;and output conjugate
        move b,y:(r4)
        move x:(r0),b
        neg a
        move a,y:(r5)
        mac -x1,x0,b    x:(r0)+n0,a
        macr -y1,y0,b  x:(r1),x1      y:(r6),y0
        subl b,a        b,x:(r4)+n4    y:(r0),b
    _lastpass
        move          a,x:(r5)+n5
        endm

```

## APPENDIX C. SINE COSINE GENERATOR

```

;
; This program originally available on the Motorola DSP bulletin board.
; It is provided under a DISCLAIMER OF WARRANTY available from
; Motorola DSP Operation, 6501 Wm. Cannon Drive W., Austin, Tx., 78735.
;
; Sine-Cosine Table Generator for FFTs.
;
; Last Update 25 Nov 86   Version 1.2
;
sincos macro    points,coef
sincos ident    1,2
;
;       sincos -      macro to generate sine and cosine coefficient
;                   lookup tables for Decimation in Time FFT
;                   twiddle factors.
;
;       points -      number of points (2 - 32768, power of 2)
;       coef  -      base address of sine/cosine table
;                   negative cosine value in X memory
;                   negative sine value in Y memory
;
; Latest revision - 25-Nov-86
;

pi      equ      3.141592654
freq    equ      2.0*pi/@cvf(points)

count   org      x:coef
        set      0
        dup      points/2
        dc       -@cos(@cvf(count)*freq)
count   set      count+1
        endm

count   org      y:coef
        set      0
        dup      points/2
        dc       -@sin(@cvf(count)*freq)
count   set      count+1
        endm

        endm      ;end of sincos macro

```

#### APPENDIX D. 16 QAM DATA FILES

The following two data files are prescaled (full scale constellation values divided by 256) and conjugated. Both data files must be loaded into the DSP prior to running QAM16ENC. They are properly formatted to be read into memory. They occupy the first 16 locations of x and y memory.

Data file '16QAMRE.DAT'

HX

00000000,0000000F  
FFF800,FFE800,FFF800,FFE800  
000800,000800,001800,001800  
FFF800,FFF800,FFE800,FFE800  
000800,001800,000800,001800

Data file '16QAMIM.DAT'

HY

00000000,0000000F  
000800,000800,001800,001800  
000800,001800,000800,001800  
FFF800,FFE800,FFF800,FFE800  
FFF800,FFF800,FFE800,FFE800

## APPENDIX E. 16 QAM ENCODER

```
; This program is an encoder for a 16 QAM system. A symbol consisting of
; four bits is read into the engwder and using a look up table outputs the
; values for the points on the constellation and are loaded into an array.
; The data files 16QAMRE.DAT and 16QAMIM.DAT must be loaded prior to
; running 16QAMEN. Once the 256 values are loaded into an array an IFFT
; is performed to generate the MFM signal.
```

```
;
; The following registers are modified:
```

```
; r2
; r3
; r4
; r5
;
```

```
; The following Data ALU Registers are modified:
```

```
; a0 a1 a
; x0 x1 y0
; b0 b1 b
;
```

qam16en

```
ident 1,1
page 132,54
opt nomd,nomex,loc
```

```
include 'sincos' ;include macro for sine cosine values
include 'ifft' ;include macro for calculating IFFT
```

```
; Define memory locations to be used in the program
```

```
start equ $100 ;starting program location
startifft equ $350 ;starting program location for IFFT
input equ 40 ;starting location of input bits
output equ 50 ;starting location of output bits
coef equ 128 ;location of coefficients for IFFT
points equ 256 ;number of points for IFFT
data equ 768 ;location of input data for IFFT
odata equ 1280 ;location of output data for IFFT
locate equ $9C4 ;location of message to be sent (hex)
```

```
sincos points,coef
opt mex
```

```

    org      p:start
    move     #locate,r3
begin
    move     #data,r4
    do       #201,cod
    move     #output,r5
    jsr      readbit
    move     r4,x0
    move     #data+100,a
    cmp      x0,a      ;check to see if 100 symbols have been read
    jseq     outzero   ;output 55 zeros, read remaining symbols
    jsr      outbit
code
    org      p:startifft
    ifft     points,data,odata,coef ;macro call to perform IFFT
;   jmp     begin

    nop
    swi

; The subroutine readbit reads the input value into memory one bit at a
; time

readbit
    move     #input+3,r2
    move     y:(r3)+,a ;read input symbol
    move     #>$1,x0
    do       #4,loop   ;symbol is read in one bit at a time
    and      x0,a      a,x1
    move     a1,x:(r2)-
    move     x1,a
    asr      a
loop
    rts

; The subroutine outbit outputs the values stored by readbit. This four
; bit symbol is used as an index into a lookup table.

outbit
    move     #input,r2
    clr      b
    clr      a
    addl     b,a
    do       #4,loop2   ;symbol read out one bit at a time
    move     x:(r2)+,b0
    addl     b,a
loop2
    move     a0,r5      ;symbol is used to index into lookup table
    nop
    move     x:(r5),x0   ;get real constellation value
    move     y:(r5),y0   ;get imaginary constellation value

```



```

    move    x0,x:(r4)          ;load real value into IFFT array
    move    y0,y:(r4)+        ;load imag value into IFFT array np
    rts

outzero
    do      #55,endzero        ;subroutine loads zeros in center
    move    #0,x0              ;55 locations of IFFT array to
    move    x0,x:(r4)          ;allow for filtering
    nop
    move    x0,y:(r4)+
endzero
    nop
    rts

```

## APPENDIX F. 16 QAM BOUNDARY FILE

The following data file BOUN16.d contains the symbol data for each bounded area used in the 16 QAM decoder. It must be loaded into the DSP prior to running 16QAMDEC.

Data file 'BOUN16.D'

HX

00000200,0000020F  
00000C,000008,000000,000004  
00000D,00000A,000001,000006  
00000E,000009,000002,000005  
00000F,00000B,000003,000007

## APPENDIX G. 16 QAM DECODER

```
; This program is a decoder for 16 QAM system. After computing the FFT
; of the received data the points are read out of the array one at a time
; and compared with boundaries on the constellation to determine the
; received point. The decoded symbols are then stored in memory. It is
; assumed that the sampled input data is loaded into the input data
; location (1280) of the FFT. If the sampled data is stored elsewhere a
; routine to load the FFT array will need to be added.
```

```
;
; The following registers are modified:
```

```
; r0    r4
; r1    r5
; r2    r6
```

```
; The following Data ALU registers are modified:
```

```
; a      b
; x0     x1
; y0     y1
```

qam16dec

```
ident    1,1
page 132,66,3,3,0
opt nomd,nomex,loc,nocex,mu,cex
```

```
include 'sincos' ;include macro for sine cosine values
include 'fft'    ;include macro for calculating FFT
```

```
org 1:$0000
```

```
location dsm 16      ;storage locations for look up table
input    dsm 16      ;storage locations for input data
```

```
endlong equ      *
org x:endlong
storr6 ds 1
org x:512
```

```
boundary1 ds 4      ;reserves four locations for boundary pts.
boundary2 ds 4      ;reserves four locations for boundary pts.
boundary3 ds 4      ;reserves four locations for boundary pts.
boundary4 ds 4      ;reserves four locations for boundary pts.
```

```
startfft equ $100    ;starting location for fft program
```

```

start    equ    $250      ;starting location for decoder program
points   equ    256      ;number of points for FFT
coef     equ    1024     ;location of coefficients for FFT
data     equ    1280     ;location of input data for FFT
odata    equ    1536     ;location of output data for FFT

```

;Full scale values for 16 QAM constellation.

```

four     equ    $200000
three    equ    $180000
two      equ    $100000
one      equ    $080000
zero     equ    $000000
mone     equ    $F80000
mtwo     equ    $F00000
mthree   equ    $e80000
mfour    equ    $e00000

```

```

sincos   points,coef
opt      mex

```

```

org      p:startfft
fft      points,data,odata,coef    ;Macro call for FFT

```

```

opt      cex
org      p:start
jsr      initialize
do       #201,_endrun
jsr      readdata
jsr      findbound
_endrun
        nop
        swi

```

;This initialization routine initializes register and modifiers  
;as well as clearing the memory.  
;The constellation is also loaded into memory here.

```

initialize
move     #$ffff,m0 ;reset register to linear addressing
move     #$ffff,m1 ;reset register to linear addressing
move     #$ffff,m2 ;reset register to linear addressing
move     #$ffff,m4 ;reset register to linear addressing
move     #$ffff,m5 ;reset register to linear addressing
move     #15,m6    ;set register for modulo 15 addressing
move     #0,r1
clr      b    #$0,r0
clr      a    r0,r5
do       #50,clrmem
move     a,x:(r0)+ b,y:(r5)+ ;clear first 50 memory locations
clrmem

```

```

move    #input,b1
move    b1,x:storr6

```

;Now load full scale values of the constellation in the table locations.

```

move    #location,r0                ;Real    Imag
move    r0,r4
move    #mone,a
move    #mone,b
move    a,x:(r0)+    b,y:(r4)+        ; -1    -1
move    #mthree,b
move    b,x:(r0)+    a,y:(r4)+        ; -3    -1
move    a,x:(r0)+    b,y:(r4)+        ; -1    -3
move    #mthree,a
move    a,x:(r0)+    b,y:(r4)+        ; -3    -3
move    #mone,b
move    #one,a
move    a,x:(r0)+    b,y:(r4)+        ; 1    -1
move    #mthree,b
move    a,x:(r0)+    b,y:(r4)+        ; 1    -3
move    #three,b
move    #mone,a
move    b,x:(r0)+    a,y:(r4)+        ; 3    -1
move    #mthree,a
move    b,x:(r0)+    a,y:(r4)+        ; 3    -3
move    #mthree,a
move    #three,b
move    #mone,x0
move    #one,y1
move    x0,x:(r0)+    y1,y:(r4)+        ; -1    1
move    x0,x:(r0)+    b,y:(r4)+        ; -1    3
move    a,x:(r0)+    y1,y:(r4)+        ; -3    1
move    a,x:(r0)+    b,y:(r4)+        ; -3    3
move    #one,a
move    #one,x0
move    #three,y1
move    x0,x:(r0)+    a,y:(r4)+        ; 1    1
move    b,x:(r0)+    a,y:(r4)+        ; 3    1
move    x0,x:(r0)+    y1,y:(r4)+        ; 1    3
move    b,x:(r0)+    y1,y:(r4)+        ; 3    3
move    #odata,x0
move    #$eff,y0
move    x0,y:$424        ;store location for input to decoder
move    y0,y:$425        ;store location for output of decoder
rts

```

; The subroutine readdata reads in the data from the output of the FFT.  
; The values are read out one point at a time. The values are compared to  
; boundaries on a partitioned constellation to determine the received point.

```

readdata
    move    y:$424,r0
    nop
    move    r0,y0
    move    #odata+100,a    ;check to see if first 100 values have been
read
    cmp     y0,a
    jseq    _delzero        ;delete 55 zeros
    move    x:storr6,r6
    move    x:(r0),a        ;input data is loaded into storage location
    move    y:(r0)+,b      ;for decoding
    move    a,x:(r6)
    move    b,y:(r6)+
    move    r6,x:storr6
    move    r0,y:$424
    rts
;
;subroutine _delzero removes the zeros installed in the encoder
;
_delzero
    move    #odata+155,r0
    nop
    rts
;
; The subroutine findbound compares the value that has been read out of
; the array to the boundries on the constellation to decode the point.
; First the magnitude alone is used to find the correct bounded area then
; the signed values are used to determine the correct quadrant is used to
; increment the boundary pointer to find the correct point.
;
findbound
    move    x:-(r6),a      ; real value is stored in a
    move    #boundary1,r2 ; load starting position for bounded values
    move    #two,y0
    cmpm    y0,a          y:(r6),b ; compare mag of real value to two
                                ; imaginary value is stored in b
    jgt     bigtwo
    cmpm    y0,b          x:(r2),x0 ; compare mag of imag value to two
    jlt     continue      ; x<2,y<2, load r2 with boundary 1 and
                                ; continue
    move    #four,x1
    cmpm    x1,b          #boundary3,r2 ; compare magnitude of imag value
    nop
    move    x:(r2),x0
    jmp     continue      ;x<2,y>2 and y<4, load r2 with boundary4

bigtwo
    cmpm    y0,b          #boundary2,r2 ;x>2 y<2
    nop

```

```

        move    x:(r2),x0
        jlt     continue                ;x>2 and x<4, y<2 load boundary2 and
continue
        cmpm    x1,b                    #boundary4,r2
        nop
        move    x:(r2),x0
        jmp     continue                ;x>2,y<4 load boundary 4 and continue

```

; This part of the routine finds the correct quadrant and updates the  
; pointer to the correct point.

```

continue
        clr     a                        x:(r6),x1
        cmp     x1,a                    y:(r6),y1
        jgt     negx
        cmp     y1,a                    #3,n2
        jgt     posxnegy
posxposy
        jmp     outputdata              ;output is in first quadrant
posxnegy
        move     x:(r2)+n2,x0           ;update r2 by 3, fourth quadrant
        jmp     outputdata
negx
        cmp     y1,a                    #1,n2
        jgt     negxnegy
negxposy
        move     x:(r2)+n2,x0           ;update r2 by 1, second quadrant
        jmp     outputdata
negxnegy
        move     #2,n2
        nop
        move     x:(r2)+n2,x0           ;update r2 by 2, third quadrant

outputdata
        move     y:$425,r0
        move     x:(r2),a
        nop
        move     a1,y:(r0)+            ;move decoded symbol to output location
        move     r0,y:$425
        rts

```

## APPENDIX H. 2/3 RATE CODE DATA FILES

The following two data files are prescaled (full scale constellation values divided by 256) and conjugated. Both data files must be loaded into the DSP prior to running 23ENCOD. They are in the proper format to be loaded into memory.

Data file '23REAL.DAT'

HX

00000000,00000007  
001000,FFF000,000800,FFF800  
FFF800,000800,FFF000,001000

Data file '23IMAG.DAT'

HY

00000000,00000007  
FFF800,000800,FFF000,001000  
FFF000,001000,FFF800,000800



## APPENDIX I. 2/3 RATE CODE ENCODER

```
; This program is an encoder for a 2/3 rate convolutional code. A symbol
; consisting of two bits is read into the encoder, combinational
; logic is used to generate the third bit then a look up table is used
; to output the values from a point on the constellation. The data files
; 23REAL.DAT and 23IMAG.DAT must first be loaded in memory prior to
; 23ENCOD. The 256 values are loaded into an array and an IFFT is
; performed to generate the MFM signal.
```

```
; The following registers are modified;
```

```
;   r0   r3
;   r1   r4
;   r2   r5
```

```
; The following Data ALU registers are modified;
```

```
;   a   a0   a1
;   b   b0
;   x0  x1
;   y0  y1
```

23encod

```
    ident 1,1
    page 132,54
    opt nomd,nomex,loc
```

```
    include 'sincos'
    include 'ifft'
```

```
start equ $100 ;starting program location
startifft equ $350 ;starting program location for IFFT
points equ 256 ;number of points for IFFT
coef equ 128 ;location of coefficients for IFFT
data equ 768 ;location of input data for IFFT
odata equ 1280 ;location of output data for IFFT
locate equ $9C4 ;starting location for message to be sent
input equ 40 ;storage locations for input bits
output equ 50 ;storage locations for encoded bits
statemen equ 60 ;storage for past bits
```

```
    sincos points,coef
    opt mex
```

```
    org p:start
    move #locate,r3
```

```

begin
    move    #data,r4
    do      #201,code
    move    #output,r5
    jsr     readbit
    jsr     encode
    move    r4,x0
    move    #data+100,a
    cmp     x0,a      ;check to see if 100 symbols have been read
    jseq    outzero   ;output 55 zeros, read remaining symbols
    jsr     outbit

code
    org     p:startifft
    ifft    points,data,odata,coef;macro call to perform IFFT
;    jmp     begin

    nop
    swi

;
; The subroutine readbit reads two bits from the message and stores them
; in memory.
;
readbit
    move    #input+1,r2
    move                                y:(r3)+,a
    move    #>$1,x0
    do      #2,loop
    and     x0,a          a,x1
    move    a1,x:(r2)-
    move    x1,a
    asr     a
loop
    rts

;
; The subroutine encode performs the convolutional encoding to generate
; a redundant bit.
;
encode
    move    #input,r0
    move    #output,r5
    move    #statemem,r1
    move    x:(r0)+,x0      ;read bit x0
    move    x:(r0)-,x1      ;read bit x1
    move    x:(r1)+,a        ;read past bit s1
    move    x:(r1)-,b        ;read past bit s2
    eor     x1,a            ;x1 eor s1
    move    a,y1
    eor     y1,b            ;x1 eor s1 eor s2 = y2
    move    x0,y:(r5)        ;store x0
    move    x:(r1)+,a        ;read past bit s1
    move    x:(r1)-,x0        ;read past bit s2

```

```

eor      x1,a                ;x1 eor s1 = y1
move     x0,x:(r1)+          ;move s2 to s1
move     x1,x:(r1)           ;move x1 to s1
move     a,x:(r0)+           ;temp store y1
move     b,x:(r0)            ;temp store y2
rts

```

; The subroutine outbit reads the three bits out of memory to form a  
; symbol. The symbols are reconstructed by reading the bits one at a  
; time added to to an empty register and shifted left until three bit  
; symbol is formedA lookup table is used to get the values for the point  
; on the constellation.

```

outbit   move      #input,r2
         clr      b
         clr      a          y:(r5),b0
         addl     b,a
         do       #2,loop2
         move     x:(r2)+,b0
         addl     b,a
loop2
         move     a0,r5      ;move symbol to r5
         nop
;
;use value in r5 to get points off the constellation
;
         move     x:(r5),x0
         move     y:(r5),y0
;
;move constellation points to IFFT array
;
         move     x0,x:(r4)
         move     y0,y:(r4)+
         nop
         rts
;
;subroutine outzero puts 55 zeros in IFFT array for filtering
;

```

```

outzero
         do       #55,endzero
         move     #0,x0
         move     x0,x:(r4)
         nop
         move     x0,y:(r4)+
endzero
         nop
         rts

```

## APPENDIX J. 2/3 RATE CODE BOUNDARY FILE

The following data file BOUN23.D contains the points on the constellation used to find the minimum distances to states after the proper quadrant is found.

Data file 'BOUN23.D

HX

00000200,0000020F

000040,000042,000044,000047

000041,000042,000044,000046

000041,000043,000045,000046

000040,000043,000045,000047

## APPENDIX K. 2/3 RATE CODE VITERBI DECODER

```

; This program is a Viterbi Decoder for a 2/3 rate convolutional encoder.
; There is a 16 time period delay which will approach the maximum possible
; gain for this type of encoder. There are 64 locations needed in memory
; (16 past time periods x 4 states = 64).
;
; The following registers are modified:
;   r0   r5
;   r1   r6
;   r2   r7
;   r4
;
; The following Data ALU registers are modified:
;   a    b    x0    y0
;   a1   b1   x1    y1
;
; The following register modifiers are used;
;   m1    n0
;   m5    n2
;   m6
;
mfm23dec
    ident    1,1
    page 132,66,3,3,0
    opt nomd,nomex,loc,nocex,mu,cex

    include 'sincos'
    include 'fft'

    org 1:$0000

period    dsm      64      ;64 storage locations
location  dsm      8       ;constellation points
input     dsm      16      ;past 16 input bits
tables    dsm      4       ;accumlated distance
temp      dsm      4       ;temp storage for distance table

endlong   equ      *
    org x:endlong
storr6    ds       1
ynow      dsm      3       ;input bits
    org y:endlong
ypast     dsm      2       ;past bits
    org x:512
boundaryl  ds       16      ;storage for boundary data
startfft  equ      $100     ;starting location for FFT

```

```

points      equ 256          ;number of points for FFT
coef        equ 1024         ;location of coefficients for FFT
data        equ 1280         ;location of sampled data for FFT
odata       equ 1536         ;output location for FFT
start       equ $250         ;starting location for decoder program

```

; Define full scale constellation values.

```

two         equ $100000
one         equ $080000
zero        equ $000000
mone        equ $F80000
mtwo        equ $F00000

```

```

large       equ .9
small       equ .1
offset      equ $000000      ;can be used to distort data

```

```

sincos      points,coef
opt mex

```

```

org p:startfft
fft points,data,odata,coef
opt cex
org p:start
jsr initialize
do #201,_endrun
jsr readdata
jsr findmindist
jsr accumdist
jsr traceback
jsr outputdata

```

\_endrun

```

nop
swi

```

;
;this initialization routine initializes register and modifiers
;as well as clearing the memory. The constellation is also loaded
;into memory here. The accumulated distance array is set so that
;state zero starts out at a value of zero and all others start out
;larger, forcing the paths to merge at the zero states.

```

;
initialize
move $ffff,m0      ;sets linear addressing
move #63,m1        ;sets modulo 63 addressing
move $ffff,m2      ;sets linear addressing
move $ffff,m4      ;sets linear addressing
move #63,m5        ;sets modulo 63 addressing
move #15,m6        ;sets modulo 16 addressing
move #0,r1

```

```

        clr      b      #$0,r0
        clr      a      r0,r5
        do #256,clrmem
        move     a,x:(r0)+ b,y:(r5)+
clrmem
        move     #tables+1,r7
        move     #$400000,a1
        rep #3
        move     a1,x:(r7)+

        move     #input,b1
        move     b1,x:storr6

        move     #odata-16,r0
        move     r0,r2
        move     #0,x0
        move     #0,y0
        do      #16,_clrreg
        move     x0,x:(r0)+
        move     y0,y:(r2)+
_clrreg
;
;Now load full scale values of the constellation in the table locations.
;

```

```

        move     #location,r0          ;Real      Imag
        move     r0,r4
        move     #two,a
        move     #one,y1
        move     #mtwo,b
        move     #mone,y0
        move     #one,x1
        move     #mone,x0
        move     a,x:(r0)+   y1,y:(r4)+   ; 2      1
        move     x1,x:(r0)+   a,y:(r4)+   ; -2     -1
        move     x0,x:(r0)+   a,y:(r4)+   ; 1      2
        move     b,x:(r0)+   y1,y:(r4)+   ; -1     -2
        move     b,x:(r0)+   y0,y:(r4)+   ; -1     2
        move     x1,x:(r0)+   b,y:(r4)+   ; 1      -2
        move     x0,x:(r0)+   b,y:(r4)+   ; 1      -2
        move     a,x:(r0)+   y0,y:(r4)+   ; 2      -1
        move     #odata,x0
        move     #$eff,y0
        move     x0,y:$424
        move     y0,y:$425
        rts

```

```

;
; readdata reads in the data from the output of the FFT. The data is read
; in as complex points on the constellation.
;

```

```

readdata
    move    y:$424,r0
    nop
    move    r0,y0
    move    #odata+100,a
    cmp     y0,a
    jseq    _delzero
    move    x:storr6,r6
    move    #>offset,x0
    move    x:(r0),a
    add     x0,a        y:(r0)+,b
    add     x0,b        a,x:(r6)
    move    b,y:(r6)+
    move    r6,x:storr6
    move    r0,y:$424
    rts

```

```

_delzero
    move    #odata+155,r0
    nop
    rts

```

```

;
; the minimum distance is found to the closest point in every state and
; stored. The values are stored so that indexing is made easier, state
; 0,2,3,1. This will greatly reduce the number of cycles needed later.
; a smoothing function is used to accumulate distances in the accumulated
; table so this minimum distance is multiplied by .1.
;

```

```

; The subroutine findmindist finds the quadrant of the received point
; which is used as a pointer into the boundary table to read the four
; closest points, one in each state.
;

```

```

findmindist
    move    #boundary1,r2
    clr     a    x:-(r6),x1
    cmp     x1,a        y:(r6),y1
    jgt     negx                ;x<0
    cmp     y1,a        #12,n2
    jgt     posxnegy
posxposy
    jmp     findist
posxnegy
    move    x:(r2)+n2,x0
    jmp     findist
negx
    cmp     y1,a        #4,n2
    jgt     negxnegy
negxposy
    move    x:(r2)+n2,x0
    jmp     findist

```



```

negxnegy
    move #8,n2
    nop
    move x:(r2)+n2,x0
;
; findist finds the distance from the received point to the points read
; from the boundary table.
;
findist
    move    x:(r2)+,r0
    move    #tables,r4
    move    x:(r0),a
    sub     x1,a      y:(r0),b
    sub     y1,b      a,x0
    mpy     x0,x0,a    b,y0
    mac     y0,y0,a    x:(r2)+,r0
    move    #small,x0  a,y0
    mpy     x0,y0,a
    move    x:(r0),a    a,y:(r4)+
    sub     x1,a      y:(r0),b
    sub     y1,b      a,x0      y:(r4)+,y0
    mpy     x0,x0,a    b,y0
    mac     y0,y0,a    x:(r2)+,r0
    move    #small,x0  a,y0
    mpy     x0,y0,a
    move    x:(r0),a    a,y:(r4)-
    sub     x1,a      y:(r0),b
    sub     y1,b      a,x0y:(r4)-,y0
    mpy     x0,x0,a    b,y0
    mac     y0,y0,a    x:(r2)+,r0
    move    #small,x0  a,y0
    mpy     x0,y0,a
    move    a,y:(r4)
    rts
;
; the accumulated distance routine adds the smallest distance from the
; previously computed table for all pathes going into a state and
; does this for all four states. Since only certain transitions are
; allowed the calculations are done in a specific order to reduce delay.
;
accumdist
    clr a    #tables,r0
    move    #$7fffff,a1
    move    r0,r4

```

```

move    #temp,r2
move    #1,m0
move    m0,m4
move    #1,n1
move    n1,n5
move    r1,r5

```

```

;find minimum distance to state zero

```

```

do    #2,statezero
move x:(r0),x0    y:(r4),b
add x0,b
cmp b,a
tge b,a          r0,r3
tge b,a          r4,r7
move x:(r0)+,x0    y:(r4)+,b
statezero
move r3,x:(r1)+n1
move a,x:(r2)+    y:(r4)+,b
clr a            r7,y:(r5)+n5
move #$7ffffff,a1

```

```

;find minimum distance to state two

```

```

do    #2,statetwo
move x:(r0),x0    y:(r4),b
add x0,b
cmp b,a
tge b,a          r0,r3
tge b,a          r4,r7
move x:(r0)+,x0    y:(r4)+,b
statetwo
move r3,x:(r1)+n1
move a,x:(r2)+    y:(r4)+,b
clr a            r7,y:(r5)+n5
move             #tables+2,r4
move             r4,r0
move             x:(r1)-n1,a
clr a            x:(r1)-,b
move #$7ffffff,a1
move r1,r5

```

```

;find minimum distance to state one

```

```

do    #2,stateone
move x:(r0),x0    y:(r4),b
add x0,b
cmp b,a
tge b,a          r0,r3
tge b,a          r4,r7

```

```

        move x:(r0)+,x0    y:(r4)-,b
stateone
        move r3,x:(r1)+n1
        move a,x:(r2)+
        clr  a              r7,y:(r5)+n5
        move #$7ffffff,a1

;find minimum distance to state three
        do #2,statethree
        move x:(r0),x0    y:(14),b
        add x0,b
        cmp b,a
        tge b,a          r0,r3
        tge b,a          r4,r7
        move x:(r0)+,x0    y:(r4)-,b
statethree
        move r3,x:(r1)+n1
        move a,x:(r2)+
        clr  a              r7,y:(r5)+n5
        move #$7ffffff,a1
        move (r4)+

;now move new accumulated distances into the accumulated distance
;table from the temporary table
;also find the min distance state and store in r4 which is no longer used

        move    #$ffff,m0
        move    #$ffff,m4
        move    #temp,r3
        move    #tables,r0
        move    #large,x1
        move    #2,n0
        do      #3,endtable
        move    x:(r3)+,x0
        mpy     x1,x0,a
        cmp     a,b          a,x:(r0)+n0
        tge     a,b          r0,r4
endtable

        move    #tables+1,r0
        do      #4,endtablex
        move    x:(r3)+,x0
        mpy     x1,x0,a
        cmp     a,b          a,x:(r0)+n0
        tge     a,b          r0,r4
endtablex

;store in r0 instead of r4

        move    r4,r0
        move    #4,n1

```

```

move    (r0)-n0
rts

```

;the traceback routine now goes back through every time period starting  
;with the current time period and finds the state from which the path  
;came from one time period previous. At the end of this search, the  
;last state found will also point to the path at that state, which is the  
;output of the trellis.

traceback

;find the displacement from the pointer to table and store value in n4

```

move    #tables,n0
move    (r1)-n1
lua     (r0)-n0,n5
move    r1,r5
do      #15,endtrace
move    (r1)-n1
move    x:(r5+n5),r0
move    r1,r5
lua     (r0)-n0,n5
endtrace
move    #location,r0
move    y:(r5+n5),a
rts

```

;the output data routine unscrambles the path order and finds one  
;of the two points on the constellation corresponding to the output state  
;which is closest to the original input at that time period.

outputdata

```

move    a,b
move    #>$b1,x0
cmp     x0,a      #>$b2,y0
teq     y0,b
cmp     y0,a      #>$b3,x0
teq     x0,b
cmp     x0,a      #>$b1,y0
teq     y0,b
move    #>$b5,x0
cmp     x0,a      #>$b7,y0
teq     y0,b
cmp     y0,a
teq     x0,b
move    b,r2
move    #tables,n2
move    x:storr6,r6
lua     (r2)-n2,n3
move    n3,a

```

```

    asl a
    asl a
    move a,n0
    move r6,r3
    lua (r0)+n0,r4
    move #>$7ffff,x1
    move r4,r0
    do #4,endout
    move x:(r3),a      y:(r6),b
    move x:(r0)+,x0    y:(r4)+,y0
    sub x0,a
    sub y0,b          a,x0
    mpy x0,x0,a        b,y0
    mac y0,y0,a
    tfr a,b            x1,a
    cmp x1,b
    tlt b,a            r0,r7
    move a,x1
endout
    clr a (r7)-
    move #location,n0
    move r7,r0
    move #f,a1
    lua (r0)-n0,r7
    move r7,x0
    and x0,a
    jsr convoldec

    move y:$425,r0
    nop
    move a0,y:(r0)+
    move r0,y:$425
    rts

```

;The subroutine convoldec decodes the received symbol by using  
;combinational logic.

```

convoldec
    move #ynow+2,r0
    move #>$1,x0
    move #ypast,r7
    do #3,loop
    and x0,a          a,x1
    move a1,x:(r0)-
    move x1,a
    asr a
loop
    move x:(r0)+,a      y:(r7)+,y0      ;read s1
    move x:(r0)+,b      y:(r7)-,y1      ;read y0 and s2
    move x:(r0)-,a      ;read y1

```

```

nop
eor y0,a
move y1,y:(r7)+      ;y1 eor s1 =x1
                      ;update past states
move a,y:(r7)-
move b,x:(r0)-
move a,x:(r0)+
clr a
clr b
do #2,loop2
move x:(r0)-,b0      ;output decoded bits
addl b,a
loop2
rts

```

## APPENDIX L. V.32 DATA FILES

The following data files are prescaled (full scale constellation values divided by 256) and conjugated. Both data files must be loaded into the DSP prior to running MFMENC. They are properly formatted to be read into memory.

Data file 'QAMREAL.DAT'

HX

00000000,0000001F  
FFE000,000000,000000,002000  
002000,000000,000000,FFE000  
FFF000,FFF000,001000,001000  
001000,001000,FFF000,FFF000  
FFE800,000800,FFE800,000800  
001800,FFF800,001800,FFF800  
000800,FFE800,000800,000800  
FFF800,001800,FFF800,FFF800

Data file 'QAMIMAG.DAT'

HY

00000000,0000001F  
FFF800,001800,FFF800,FFF800  
000800,FFE800,000800,000800  
FFE800,000800,FFE800,000800  
001800,FFF800,001800,FFF800  
001000,001000,FFF000,FFF000  
FFF000,FFF000,001000,001000  
FFE000,000000,000000,002000  
002000,000000,000000,FFE000

## APPENDIX M. V.32 ENCODER

```
; This is a an encoder for V.32 standard with differential encoding.
; The encoder can also be used with the differential removed by commenting
; out the call to diff.
```

mfmencod

```
    ident    1,1
    page     132,54
    opt      nomd,nomex,loc
```

```
    include  'sincos'
    include  'ifft'
```

```
    org  x:$40
statemem    ds    3           ;set 3 locations for past states
input       ds    4           ;set up 4 locations for input bits
```

```
    org  y:$40
ylpast     ds    2           ;set up two locations for diff encoder
output      ds    1           ;output of convolutional encoder
```

```
start       equ    $100       ;starting location for encoder
startifft   equ    $350       ;starting location for IFFT
points      equ    256        ;number of points for IFFT
odata       equ    1280       ;output of IFFT
data        equ    768        ;input data for IFFT
coef        equ    128        ;location for coefficients for IFFT
locate      equ    $9C4       ;starting location for message
```

```
sincos      points,coef
opt          mex
```

```
    org      p:start
    move     #ylpast,r5
    move     #statemem,r3
    move     #locate,r6
```

begin

```
    move     #data,r7
    do       #201,code         ;reads 201 message symbols
    move     #output,r4
    jsr      readbit
    jsr      diff
    jsr      encode
```



```

        move    r7,x0
        move    #data+100,a
        cmp     x0,a                ;checks if first 100 symbols read
        jseq    outzero             ;outputs 55 zeros
        jsr     outbit
code
        org     p:startifft
        ifft     points,data,odata,coef
;        jmp     begin

        nop
        swi

;
;subroutine readbit reads in the four bit symbol one bit at a time
;
readbit
        move    #input+3,r2
        move     y:(r6)+,a
        move    #>$1,x0
        do      #4,loop
        and     x0,a                a,x1
        move    a1,x:(r2)-
        move    x1,a
        asr     a
loop
        rts

;
;subroutine diff differentially encodes the two most significant bits
;
diff
        move    #input,r1
        move     y:(r5)+,y0
        move     x:(r1)+,a        y:(r5)-,y1
        move     x:(r1)-,b
        eor     y0,a                a,x0
        eor     y1,b                a,x1
        move     x0,a
        and     y0,a                b,y1
        eor     y1,a                x1,b
        move     b,x:(r1)+        b,y:(r5)+
        move     a,x:(r1)         a,y:(r5)-
        rts

;
;subroutine encode convolutionally encodes the four bits to generate a
;fifth bit
;
encode
        move     #input,r0

```

```

    move    #output,r4
    move    #statemem,r1
    move    x:(r0)+,x1
    move    x:(r1)+,a
    move    a,y:(r4)
    and x1,a      x:(r0),x0
    move x:(r1)-,b
    eor x0,b      a,y0
    eor y0,b      b,y1
    move b,x:(r1)+ y:(r4),b
    and y1,b      x0,a
    move (r1)+
    eor x1,a      x:(r1),x0
    eor x0,a      y:(r4),y1
    move b,y0
    eor y0,a      y1,x:(r1)-
    move a,x:(r1)+
    rts
;
;subroutine outbit reads the five bit symbol and uses it to index into the
;lookup table to get the values of the point on the constellation
;
outbit    move    #input,r2
    clr b
    clr a      y:(r4),b0
    addl b,a
    do #4,loop2
    move x:(r2)+,b0
    addl b,a
loop2
    move    a0,r4
    nop
    move x:(r4),x0
    move    y:(r4),y0
;
;move the values read from the constellation to the input array for the
;IFFT
;
    move x0,x:(r7)
    move    y0,y:(r7)+
    nop
    rts
;
;subroutine outzero loads 55 zeros into the IFFT array for filtering
;
outzero
    do #55,endzero
    move #0,x0
    move x0,x:(r7)
    nop

```

move x0,y:(r7)+  
endzero  
nop  
rts

## APPENDIX N. V.32 BOUNDARY FILE

This data file BOUND.D contains the eight closest points (one in each state) to each of the 52 bounded areas used in the partitioned constellation. It must be loaded prior to using MFMDIFDE.

Data file 'BOUND.D'

HX

00000200,0000039F  
000082,000086,00008B,00008D  
000093,000095,00009A,00009E  
000082,000086,000089,00008F  
000093,000095,00009A,00009E  
000082,000086,000089,00008F  
000091,000097,00009A,00009E  
000082,000086,00008B,00008D  
000091,000097,00009A,00009E  
000082,000086,00008B,00008D  
000093,000094,00009A,00009D  
000082,000086,000089,00008F  
000092,000095,000099,00009E  
000082,000086,000089,00008F  
000090,000097,000099,00009E  
000082,000086,00008B,00008D  
000091,000096,00009A,00009D  
000083,000084,00008B,00008D  
000093,000094,00009A,00009D  
000080,000087,000089,00008F  
000092,000095,000099,00009E  
000080,000087,000089,00008F  
000090,000097,000099,00009E  
000083,000084,00008B,00008D  
000091,000096,00009A,00009D  
000082,000085,00008A,00008D  
000093,000095,00009A,00009E  
000082,000085,000088,00008F  
000093,000095,00009A,00009E  
000081,000086,000089,00008E  
000091,000097,00009A,00009E  
000081,000086,00008B,00008C  
000091,000097,00009A,00009E  
000082,000085,00008A,00008D  
000093,000094,00009A,00009D  
000082,000085,000088,00008F  
000092,000095,000099,00009E  
000081,000086,000089,00008E

000090,000097,000099,00009E  
000081,000086,00008B,00008C  
000091,000096,00009A,00009D  
000082,000085,00008A,00008D  
000093,000095,000098,00009F  
000082,000085,000088,00008F  
000093,000095,000098,00009F  
000081,000086,000089,00008E  
000091,000097,00009B,00009C  
000081,000086,00008B,00008C  
000091,000097,00009B,00009C  
000083,000084,00008A,00008D  
000093,000094,00009A,00009D  
000080,000087,000088,00008F  
000092,000095,000099,00009E  
000080,000087,000089,00008E  
000090,000097,000099,00009E  
000083,000084,00008B,00008C  
000091,000096,00009A,00009D  
000082,000085,00008A,00008D  
000093,000094,000098,00009F  
000082,000085,000088,00008F  
000092,000095,000098,00009F  
000081,000086,000089,00008E  
000090,000097,00009B,00009C  
000081,000086,00008B,00008C  
000091,000096,00009B,00009C  
000083,000085,00008A,00008D  
000093,000094,000098,00009D  
000080,000085,000088,00008F  
000092,000095,000099,00009F  
000081,000087,000089,00008E  
000090,000097,000099,00009C  
000081,000084,00008B,00008C  
000091,000096,00009B,00009D  
000082,000085,00008A,00008D  
000093,000094,000098,00009D  
000082,000085,000088,00008F  
000092,000095,000099,00009F  
000081,000086,000089,00008E  
000090,000097,000099,00009C  
000081,000086,00008B,00008C  
000091,000096,00009B,00009D  
000083,000085,00008A,00008D  
000093,000094,00009A,00009D  
000080,000085,000088,00008F  
000092,000095,000099,00009E  
000081,000087,000089,00008E  
000090,000097,000099,00009E  
000081,000084,00008B,00008C  
000091,000096,00009A,00009D

000083,000084,00008A,00008D  
000093,000094,000098,00009D  
000080,000087,000088,00008F  
000092,000095,000099,00009F  
000080,000087,000089,00008E  
000090,000097,000099,00009C  
000083,000084,00008B,00008C  
000091,000096,00009B,00009D  
000083,000085,00008A,00008D  
000093,000094,000098,00009F  
000080,000085,000088,00008F  
000092,000095,000098,00009F  
000081,000087,000089,00008E  
000090,000097,00009B,00009C  
000081,000084,00008B,00008C  
000091,000096,00009B,00009C

## APPENDIX O. V.32 VITERBI DECODER

```

;This program is a Viterbi Decoder for V.32. There is a 16
;time period delay which will approach the maximum possible
;gain for this type of encoder. If the differential encoder
;was not used in the encoder than the call to diff must be
;commented out.
;
;There are 128 memory locations allocated for path memory (8 states x 16
;time periods =128 locations). The full scale constellation values are
;loaded into memory during the initialization routine.
;
mfmdecod
    ident    1,1
    page 132,66,3,3,0
    opt nomd,nomex,loc,nocex,mu,cex

    include 'sincos'
    include 'fft'

    org 1:$0000

period    dsm        128        ;128 locations for path memory
location dsm         32        ;32 locations for constellation points
input     dsm         16        ;16 locations for input points
tables    dsm         8         ;8 locations for accumulated distance table
temp       dsm         8         ;8 temp locations for distances
endlong    equ        *
    org x:endlong
storr6     ds 1
ynow        ds 4                ;4 locations for input bits
    org y:endlong
ypast       ds 2                ;2 past bits for differential decoder

;
;13 boundary tables with 8 points in each of the 4 quadrants
;
    org x:512
boundry1     ds 32
boundry2     ds 32
boundry3     ds 32
boundry4     ds 32
boundry5     ds 32
boundry6     ds 32
boundry7     ds 32
boundry8     ds 32

```

```

boundary9      ds    32
boundary10     ds    32
boundary11     ds    32
boundary12     ds    32
boundary13     ds    32

```

```

startfft      equ     $100      ;starting location for FFT routine
points        equ     256      ;number of points for FFT
coef          equ     1024     ;location of FFT coefficients
data          equ     1280     ;location of sampled data
odata         equ     1536     ;output data from FFT
start         equ     $250     ;starting location of decoder

```

```

;
;Load in full scale constellation values
;

```

```

four          equ     $200000
three         equ     $180000
two           equ     $100000
one           equ     $080000
zero          equ     $000000
mone          equ     $F80000
mtwo          equ     $F00000
mthree        equ     $e80000
mfour         equ     $e00000

```

```

large         equ     .9
small         equ     .1
offset        equ     $000000

```

```

sincos points,coef
opt mex

```

```

org p:startfft
fft points,data,odata,coef
opt cex
org p:start
jsr initialize
do #217,_endrun
jsr readdata
jsr findmindist
jsr accumdist
jsr traceback
jsr outputdata
_endrun
nop
swi

```

```

;
; this initialization routine initializes register and
; modifiers as well as clearing the memory. The constellation
; is also loaded into memory here. The accumulated distance
; array is set so that state zero starts out at a value of

```



```

; zero and all others start out larger, forcing the paths
; to merge at the zero states.
;
initialize
    move #$ffff,m0          ;linear addressing
    move #127,m1             ;modulo 127 addressing
    move #$ffff,m2          ;linear addressing
    move #$ffff,m4          ;linear addressing
    move #127,m5             ;modulo 127 addressing
    move #15,m6              ;modulo 15 addressing
    move #0,r1
    clr b    #$0,r0
    clr a    r0,r5
    do #256,clrmem
    move a,x:(r0)+    b,y:(r5)+
clrmem
    move    #tables+1,r7
    move    #$400000,a1
    rep #7
    move    a1,x:(r7)+

    move    #input,b1
    move    b1,x:storr6

    move    #odata-16,r0
    move    r0,r2
    move    #0,x0
    move    #0,y0
    do    #16,_clrreg
    move    x0,x:(r0)+
    move    y0,y:(r2)+
_clrreg

; Now load full scale values of the constellation in the table
; location.

    move    #location,r0
    move    r0,r4
    move    #mfour,a          ;Real    Imag
    move    #one,b
    move    a,x:(r0)+    b,y:(r4)+    ; -4    1
    move    #zero,a
    move    #mthree,b
    move    a,x:(r0)+    b,y:(r4)+    ; 0    -3
    move    #one,b
    move    a,x:(r0)+    b,y:(r4)+    ; 0    1
    move    #four,a
    move    a,x:(r0)+    b,y:(r4)+    ; 4    1
    move    #mone,b
    move    a,x:(r0)+    b,y:(r4)+    ; 4    -1

```

move	#zero,a			
move	#three,b			
move	a,x:(r0)+	b,y:(r4)+	; 0	3
move	#mone,b			
move	a,x:(r0)+	b,y:(r4)+	; 0	-1
move	#mfour,a			
move	a,x:(r0)+	b,y:(r4)+	; -4	-1
move	#mtwo,a			
move	#three,b			
move	#mone,y1			
move	a,x:(r0)+	b,y:(r4)+	; -2	3
move	a,x:(r0)+	y1,y:(r4)+	; -2	-1
move	#two,a			
move	a,x:(r0)+	b,y:(r4)+	; 2	3
move	a,x:(r0)+	y1,y:(r4)+	; 2	-1
move	#one,b			
move	#mthree,y1			
move	a,x:(r0)+	y1,y:(r4)+	; 2	-3
move	a,x:(r0)+	b,y:(r4)+	; 2	1
move	#mtwo,a			
move	a,x:(r0)+	y1,y:(r4)+	; -2	-3
move	a,x:(r0)+	b,y:(r4)+	; -2	1
move	#one,a			
move	a,x0			
move	#mthree,a			
move	#two,b			
move	b,y0			
move	#mtwo,b			
move	a,x:(r0)+	b,y:(r4)+	; -3	-2
move	x0,x:(r0)+	b,y:(r4)+	; 1	-2
move	a,x:(r0)+	y0,y:(r4)	; -3	2
move	x0,x:(r0)+	y0,y:(r4)+	; 1	2
move	#three,a			
move	a,x0			
move	#mone,a			
move	x0,x:(r0)+	y0,y:(r4)+	; 3	2
move	a,x:(r0)+	y0,y:(r4)+	; -1	2
move	x0,x:(r0)+	b,y:(r4)+	; 3	-2
move	a,x:(r0)+	b,y:(r4)+	; -2	-1
move	#one,a			
move	#zero,b			
move	b,y0			
move	#four,b			
move	a,x:(r0)+	b,y:(r4)+	; 1	4
move	#mthree,x0			
move	x0,x:(r0)+	y0,y:(r4)+	; -3	0
move	a,x:(r0)+	y0,y:(r4)+	; 1	0
move	#mfour,b			
move	a,x:(r0)+	b,y:(r4)+	; 1	-4
move	#mone,a			
move	a,x:(r0)+	b,y:(r4)+	; -1	-4

```

        move    #three,x0
        move    x0,x:(r0)+    y0,y:(r4)+    ; 3      0
        move    a,x:(r0)+    y0,y:(r4)+    ; -1     0
        move    #four,b
        move    a,x:(r0)+    b,y:(r4)+    ; -1     4
        move    #odata,x0
        move    #seff,y0
        move    x0,y:$424
        move    y0,y:$425
        rts
;
;readdata reads in the data from the output of the FFT.
;
readdata
        move    y:$424,r0
        nop
        move    r0,y0
        move    #odata+100,a
        cmp     y0,a
        jseq    _delzero
        move    x:storr6,r6
        move    #>offset,x0
        move    x:(r0),a
        add     x0,a          y:(r0)+,b
        add     x0,b          a,x:(r6)
        move    b,y:(r6)+
        move    r6,x:storr6
        move    r0,y:$424
        rts

_delzero
        move    #odata+155,r0
        nop
        rts
;
;the minimum distance is found to the closest point in every
; state and stored. The values are stored so that indexing is
; made easier, state 0,2,3,1,4,7,6,5. This will greatly reduce
; the number of cycles needed later. A smoothing function is
; used to accumulate distances in the accumulated table so
; this minimum distance is multiplied by .1.
;
;The subroutine findmindist compares the received points to boundaries
;on the constellation. Once a bounded area is found the closest eight
;points are read out of the boundary data file and used to update the
;path distances.
;
findmindist

        move    x:-(r6),a
        move    #one,x0

```

```

    cmpm x0,a      y:(r6),b
    jgt bigone
    cmpm x0,b      #boundry1,r2
    jlt continue
    move #two,x1
    cmpm x1,b      #boundry4,r2
    jlt continue
    move          #boundry6,r2
    jmp continue
bigone  move #two,x1
    cmpm x1,a
    jgt bigtwo
    cmpm x0,b      #boundry2,r2
    jlt continue
    cmpm x1,b      #boundry5,r2
    jlt continue
bigtwo  cmpm x0,b      #boundry3,r2
    jlt continue
    abs a          #two,y0
    abs b          a,x1
    sub y0,a      b,y1
    sub x0,b
    cmpm a,b      y1,b
    jgt greateryl
    cmp y0,b      #boundry7,r2
    jlt continue
    move          #boundry12,r2
    jmp continue
greateryl
    sub y0,b      x1,a
    sub x0,a
    cmpm a,b      x1,a
    jgt greatery2
    cmp y0,a      #boundry10,r2
    jlt continue
    move y1,b
    cmp y0,b      #boundry11,r2
    jlt continue
    move          #boundry9,r2
    jmp continue
greatery2
    cmp y0,a      #boundry8,r2
    jlt continue
    move          #boundry13,r2

```

;x>1  
 ;x<1,y<1, load r2 with boundry 1  
 ;and continue  
 ;x<1,y>1andy<2, load r2 with  
 ;bcundry4, go on  
 ;x<1,y>2, load r2 with boundry6  
 ;and continue  
 ;x>2, jmp to that case  
 ;x>1 and x<2, y<1 load boundry2  
 ;and continue  
 ;x>1,y<2 load boundry 5 and  
 ;continue  
 ;x>2 and y<1 so load boundry3  
 ;and continue

```

continue
    clr  a          x:(r6),x1
    cmp  x1,a        y:(r6),y1
    jgt  negx
    cmp  y1,a        #24,n2
    jgt  posxnegy
posxposy
    jmp  findist
posxnegy
    move x:(r2)+n2,x0          ;update r2 by 24
    jmp  findist
negx
    cmp  y1,a          #8,n2
    jgt  negxnegy
negxposy
    move x:(r2)+n2,x0          ;update r2 by 8
    jmp  findist
negxnegy
    move x:(r2)+n2,x0          ;update r2 by 16
    move x:(r2)+n2,x0

```

;

;The subroutine findist finds the euclidean distance between the received point and the eight points read out of the boundary table. The x and y coordinates are subtracted, squared and added. The square root is not performed.

```

findist
    move x:(r2)+,r0
    move #tables,r4
    move x:(r0),a
    sub  x1,a          y:(r0),b
    sub  y1,b          a,x0
    mpy  x0,x0,a        b,y0
    mac  y0,y0,a        x:(r2)+,r0
    move #small,x0      a,y0
    mpy  x0,y0,a
    move x:(r0),a        a,y:(r4)+
    sub  x1,a          y:(r0),b
    sub  y1,b          a,x0    y:(r4)+,y0
    mpy  x0,x0,a        b,y0
    mac  y0,y0,a        x:(r2)+,r0
    move #small,x0      a,y0
    mpy  x0,y0,a        y:(r4)+,b
    move x:(r0),a        a,y:(r4)-
    sub  x1,a          y:(r0),b
    sub  y1,b          a,x0    y:(r4)-,y0
    mpy  x0,x0,a        b,y0
    mac  y0,y0,a        x:(r2)+,r0
    move #small,x0      a,y0
    mpy  x0,y0,a

```

```

move x:(r0),a      a,y:(r4)+
sub  x1,a          y:(r0),b
sub  y1,b          a,x0
mpy  x0,x0,a       b,y0
mac  y0,y0,a       x:(r2)+,r0
move #small,x0     a,y0
mpy  x0,y0,a
move x:(r0),a      a,y:(r4)+
sub  x1,a          y:(r0),b
sub  y1,b          a,x0   y:(r4)+,y0
mpy  x0,x0,a       b,y0
mac  y0,y0,a       x:(r2)+,r0
move #small,x0     a,y0
mpy  x0,y0,a
move x:(r0),a      a,y:(r4)+
sub  x1,a          y:(r0),b
sub  y1,b          a,x0   y:(r4)+,y0
mpy  x0,x0,a       b,y0
mac  y0,y0,a       x:(r2)+,r0
move #small,x0     a,y0
mpy  x0,y0,a
move x:(r0),a      a,y:(r4)-
sub  x1,a          y:(r0),b
sub  y1,b          a,x0
mpy  x0,x0,a       b,y0
mac  y0,y0,a       x:(r2)+,r0
move #small,x0     a,y0
mpy  x0,y0,a
move a,y:(r4)
rts

```

;the accumulated distance routine adds the smallest distance  
;from the previously computed table for all pathes going into  
;a state and does this for all eight states.

```

accumdist
clr  a    #tables,r0
move #7ffff,a1
move  r0,r4
move  #temp,r2
move  #3,m0
move  m0,m4
move  #2,n1
move  n1,n5

```

```

        move    r1,r5

;Distances in the accumulated distance table are added to distances in the
;path table and compared for the four paths. This is done by incrementing
;through a specially ordered path table.

;find minimum distance to state zero
do #4,statezero
    move x:(r0),x0    y:(r4),b
    add x0,b
    cmp b,a
    tge b,a    r0,r3
    tge b,a    r4,r7
    move x:(r0)+,x0    y:(r4)+,b
statezero
    move r3,x:(r1)+n1
    move a,x:(r2)+    y:(r4)+,b
    clr a    r7,y:(r5)+n5
    move #$7ffffff,a1

;find minimum distance to state two
do #4,statetwo
    move x:(r0),x0    y:(r4),b
    add x0,b
    cmp b,a
    tge b,a    r0,r3
    tge b,a    r4,r7
    move x:(r0)+,x0    y:(r4)-,b
statetwo
    move r3,x:(r1)+n1
    move a,x:(r2)+    y:(r4)+,b
    clr a    r7,y:(r5)+n5
    move #$7ffffff,a1

;find minimum distance to state four
do #4,statefour
    move x:(r0),x0    y:(r4),b
    add x0,b
    cmp b,a
    tge b,a    r0,r3
    tge b,a    r4,r7
    move x:(r0)+,x0    y:(r4)+,b
statefour
    move r3,x:(r1)+n1
    move a,x:(r2)+    y:(r4)+,b
    clr a    r7,y:(r5)+n5
    move #$7ffffff,a1

;find minimum distance to state six

```

```

        do #4,statezsix
        move x:(r0),x0      y:(r4),b
        add x0,b
        cmp b,a
        tge b,a      r0,r3
        tge b,a      r4,r7
        move x:(r0)+,x0      y:(r4)-,b
statezsix
        move r3,x:(r1)-n1
        move a,x:(r2)+
        move r7,y:(r5)
        move #tables+4,r4
        move r4,r0
        move x:(r1)-n1,a
        clr a      x:(r1)-,b
        move #$7fffff,a1
        move r1,r5

;find minimum distance to state one
        do #4,stateone
        move x:(r0),x0      y:(r4),b
        add x0,b
        cmp b,a
        tge b,a      r0,r3
        tge b,a      r4,r7
        move x:(r0)+,x0      y:(r4)+,b
stateone
        move r3,x:(r1)+n1
        move a,x:(r2)+      y:(r4)+,b
        clr a      r7,y:(r5)+n5
        move #$7fffff,a1

;find minimum distance to state three
        do #4,statethree
        move x:(r0),x0      y:(r4),b
        add x0,b
        cmp b,a
        tge b,a      r0,r3
        tge b,a      r4,r7
        move x:(r0)+,x0      y:(r4)-,b
statethree
        move r3,x:(r1)+n1
        move a,x:(r2)+      y:(r4)+,b
        clr a      r7,y:(r5)+n5
        move #$7fffff,a1
        move (r4)+

;find minimum distance to state five
        do #4,statefive
        move x:(r0),x0      y:(r4),b
        add x0,b

```



```

        cmp b,a
        tge b,a      r0,r3
        tge b,a      r4,r7
        move x:(r0)+,x0    y:(r4)-,b
statefive
        move r3,x:(r1)+n1
        move a,x:(r2)+    y:(r4)-,b
        clr a    r7,y:(r5)+n5
        move #$7fffff,a1

;find minimum distance to state seven
        do #4,stateseven
        move x:(r0),x0    y:(r4),b
        add x0,b
        cmp b,a
        tge b,a      r0,r3
        tge b,a      r4,r7
        move x:(r0)+,x0    y:(r4)+,b
stateseven
        move r3,x:(r1)+
        move a,x:(r2)+    y:(r4)+,b
        clr b    r7,y:(r5)+
        move #$7fffff,b1

;now move new accumulated distances into the accumulated
;distance table from the temporary table also find the min
;distance state and store in r4 which is no longer used

        move #$ffff,m0
        move #$ffff,m4
        move #temp,r3
        move #tables,r0
        move #large,x1
        move #2,n0
        do #4,endtable
        move x:(r3)+,x0
        mpy x1,x0,a
        cmp a,b      a,x:(r0)+n0
        tge a,b      r0,r4
endtable
        move #tables+1,r0
        do #4,endtablex
        move x:(r3)+,x0
        mpy x1,x0,a
        cmp a,b      a,x:(r0)+n0
        tge a,b      r0,r4
endtablex
;
;store in r0 instead of r4
;
        move    r4,r0

```

```

move    #8,n1
move    (r0)-n0
rts

```

```

;the traceback routine now goes back through every time period
;starting with the current time period and finds the state
;from which the path came from one time period previous. At
;the end of this search, the last state found will also point
;to the path at that state, which is the output of the
;trellis.

```

traceback

```

;find the displacement from the pointer to table and store
;value in n4

```

```

        move #tables,n0
        move (r1)-n1
        lua (r0)-n0,n5
        move r1,r5
        do #15,endtrace
        move (r1)-n1
        move x:(r5+n5),r0
        move r1,r5
        lua (r0)-n0,n5
endtrace
        move #location,r0
        move y:(r5+n5),a
        rts

```

```

;the output data routine unscrambles the path order and finds
;one of the four points on the constellation corresponding to
;the output state which is closest to the original input at
;that time period.

```

outputdata

```

move a,b
move          #>$b1,x0
cmp  x0,a     #>$b2,y0
teq  y0,b
cmp  y0,a     #>$b3,x0
teq  x0,b
cmp  x0,a     #>$b1,y0
teq  y0,b
move          #>$b5,x0
cmp  x0,a     #>$b7,y0
teq  y0,b
cmp  y0,a
teq  x0,b
move w,r2

```

```

move #tables,n2
move x:storr6,r6
lua (r2)-n2,n3
move n3,a
asl a
asl a
move a,n0
move r6,r3
lua (r0)+n0,r4
move #>$7ffff,x1
move r4,r0
do #4,endout
move x:(r3),a      y:(r6),b
move x:(r0)+,x0    y:(r4)+,y0
sub x0,a
sub y0,b      a,x0
mpy x0,x0,a  b,y0
mac y0,y0,a
tfr a,b      x1,a
cmp x1,b
tlt b,a      r0,r7
move a,x1
endout
clr a (r7)-
move #location,n0
move r7,r0
move #f,a1
lua (r0)-n0,r7
move r7,x0
and x0,a
jsr diff
move y:$425,r0
nop
move a0,y:(r0)+
move r0,y:$425
rts

```

```

;
;The subroutine diff differentially decodes the two most significant bits.
;Each bit is stored in its own memory and the bits are decoded using
;Q1n = Y1n EOR Y1n-1, Q2n = (Q1n AND Y1n-1) EOR Y2n-1 EOR Y2n. The four
;bit symbol is formed and output.
;

```

```

diff
move #ynow+3,r0
move #>$1,x0
move #ypast,r7
do #4,diffloop1
and x0,a      a,x1
move          a1,x:(r0)-
move x1,a
asr a

```

```

diffloop1
    move x:(r0)+,a      y:(r7)+,y0
    move x:(r0)+,a      y:(r7)-,y1
    move x:(r0)-,b      a,y:(r7)+
    move                b,y:(r7)-
    eor y0,a            a,x0
    eor y1,b            a,x1
    and y0,a            b,y1
    eor y1,a            x1,b
    move                b,x:(r0)+
    move                a,x:(r0)-
    clr a
    clr b
    do #4,diff2
    move                x:(r0)+,b0
    addl b,a
diff2
    rts

```

#### LIST OF REFERENCES

1. Moose, P.H., *Theory of Multi-Frequency Modulation (MFM) Digital Communications*, Technical Report No. NPS 62-89-019, Naval Postgraduate School, Monterey, May 1989.
2. Ungerboeck, G., "Trellis-Coded Modulation with Redundant Signal Sets," *IEEE Communication Magazine*, vol. 25, pp. 5-21, February 1987.
3. Thapar, H. K., "Real-Time Application of Trellis Coding to High-Speed Voiceband Data Transmission," *IEEE Journal on Selected Areas in Communications*, vol. SAC-2, No. 5, pp. 648-657, September 1984.
4. Lin, S., and Costello, D. J. Jr., *Error Control Coding*, Prentice Hall, 1983.
5. Motorola Inc., *DSP56001, 56-Bit General Purpose Digital Signal Processor*, 1988.
6. Motorola Inc., *DSP56000/DSP56001 Digital Signal Processor User's Manual*, REV. 2, 1990.
7. Gantenbein, T. K., *Implementation of Multi-Frequency Modulation on an Industry Standard Computer*, Master's Thesis, Naval Postgraduate School, Monterey, California, September 1989.
8. Messer, D. D., *Convolutional Encoding and Viterbi Decoding Using the DSP 56001 with a V.32 Modem Trellis Example*, Motorola Inc., 1989.
9. Childs, R. D., *High Speed Output Interface for a Multi-Frequency Quaternary Phase Shift Keying Signal on an Industry Standard Computer*, Master's Thesis, Naval Postgraduate School, Monterey, California, December 1988.

## BIBLIOGRAPHY

Ariel Corporation, *Operating Manual for the PC-56 DSP Coprocessor Board*, 1989.

Ariel Corporation, *Operating Manual for the BUG-56 Monitor Debugger for Ariel's DSP56001 Based DSP Boards*, August 1989.

Bingham, J. A. C., "Multicarrier Modulation for Data Transmission: An Idea Whose Time has Come," *IEEE Communication Magazine*, pp. 5-14, May 1990.

Cimini, L. J. Jr., "Analysis and Simulation of a Digital Mobile Channel Using Orthogonal Frequency Division Multiplexing," *IEEE Transactions on Communication*, pp. 665-675, July 1985.

Hirosaki, B., "An Orthogonally Multiplexed QAM System Using the Discrete Fourier Transform," *IEEE Transactions on Communications*, pp. 982-989, July 1981.

Porter G. C., " Error Distribution and Diversity Performance of a Frequency-Differential PSK HF Modem," *IEEE Transactions on Communication Technology*, pp. 567-575 August 1968.

Weinstein, S. B. and Ebert, P. M., "Data Transmission by Frequency-Division Multiplexing Using the Discrete Fourier Transform," *IEEE Transactions on Communication Technology*, pp 628-634, October 1971.

### INITIAL DISTRIBUTION LIST

- |   |   |
|---|---|
| 1. Defense Technical Information Center<br>Cameron Station<br>Alexandria, Virginia 22304-6145   | 2 |
| 2. Library, Code 52<br>Naval Postgraduate School<br>Monterey, California 93943-5002   | 2 |
| 3. Department Chairman, Code EC<br>Department of Electrical and Computer Engineering<br>Naval Postgraduate School<br>Monterey, California 93943-5100      | 1 |
| 4. Professor P. H. Moose, Code EC/Me<br>Department of Electrical and Computer Engineering<br>Naval Postgraduate School<br>Monterey, California 93943-5100 | 6 |
| 4. Professor G. A. Myers, Code EC/Mv<br>Department of Electrical and Computer Engineering<br>Naval Postgraduate School<br>Monterey, California 93943-5100 | 1 |
| 5. Professor T. T. Ha, Code EC/Ha<br>Department of Electrical and Computer Engineering<br>Naval Postgraduate School<br>Monterey, California 93943-5100    | 1 |
| 6. Lieutenant J. W. Wisniewski, U.S.N.<br>RD#7 Box 7102<br>Moscow, Pennsylvania 18444   | 1 |